8-31-2019

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Estuarine, Coastal and Shelf Science 224 (2019) 117–137

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Drivers and impacts of water level fluctuations in the Mississippi River delta: Implications for delta restoration

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ABSTRACT

This review synthesizes the knowledge regarding the environmental forces affecting water level variability in the coastal waters of the Mississippi River delta and relates these fluctuations to planned river diversions. Water level fluctuations vary significantly across temporal and spatial scales, and are subject to influences from river flow, tides, vegetation, atmospheric forcing, climate change, and anthropogenic activities. Human impacts have strongly affected water level variability in the Mississippi River delta and other deltas worldwide. Collectively, the research reviewed in this article is important for enhancing environmental, economic, and social resilience and sustainability by assessing, mitigating, and adapting to geophysical changes that will cascade to societal systems in the coming decades in the economically and environmentally important Mississippi River delta. Specifically, this information provides a context within which to evaluate the impacts of diversions on the hydrology of the Mississippi delta and creates a benchmark for the evaluation of the impact of water level fluctuations on coastal restoration projects worldwide.

1. Introduction

Coastal regions, home to 1.2 billion people worldwide and epicenters of economic activity (Nicholls and Small, 2002), are vulnerable to a myriad of environmental and anthropogenic stressors. The deltas of the world have enjoyed a period of general growth over the last several thousand years (Day et al., 2016a), but increased relative sea level rise (RSLR) rates and modifications by humans have caused many systems to reverse course and enter degradational phases (Stanley and Warne, 1998). For example, the Nile River Delta has experienced such significant coastal erosion, saline intrusion, and wetland loss that the system is no longer considered an active delta (Stanley and Warne, 1998). Since the 1930s, the Mississippi River delta (MRD) in coastal Louisiana has been a striking example of the rate at which coastal systems can degrade. Over the last century, the MRD in Louisiana has lost about 5000 km^2 of coastal wetlands at rates as high as 100 km^2 per year (Gagliano et al., 1981; Britsch and Dunbar, 1993; Boesch et al., 1994; Day et al., 2000; Couvillion et al., 2017). Coastal wetland loss in Louisiana is the result of a complex interplay of factors including rising sea levels, subsidence, fluid extraction, canal construction, and wave erosion, among others, but many researchers point to the isolation of most wetland environments from sediment-laden Mississippi River water as a major driver of wetland degradation in the MRD (Day et al., 2000, 2007; Paola et al., 2011; Blum and Roberts, 2012; Twilley et al., 2016). To combat coastal degradation, a $50 billion management plan for coastal Louisiana called the Coastal Master Plan (CPRA, 2017) includes efforts to build new land through engineered riverine sediment diversions, which aim to reintroduce sediment- and nutrient-laden river water to deteriorating wetlands. Riverine sediment diversions are designed to facilitate sediment deposition and land-building through natural processes (Paola et al., 2011; Temmerman and Kirwan, 2015). The success of restoration and protection initiatives hinges on a comprehensive understanding of the processes influencing water level fluctuations in the region. Since basin water levels exert a strong control on coastal open-channel hydraulics (Chow, 1959), water level fluctuations regulate the transport of both solids and solutes and have major implications for restoration management and design. This review details the important environmental forcings that modulate water levels throughout the various regions of the MRD in coastal Louisiana (Fig. 1) and discusses the implications for coastal restoration practices, with a specific focus on riverine sediment diversions. We draw on information from the MRD to summarize the spatial and temporal patterns in coastwide water level variability, currently operating diversions, and subdelta lobe development to discuss the water level and hydrologic

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https://doi.org/10.1016/j.ecss.2019.04.020
Received 27 July 2018; Received in revised form 14 March 2019; Accepted 14 April 2019
Available online 24 April 2019
0272-7714/

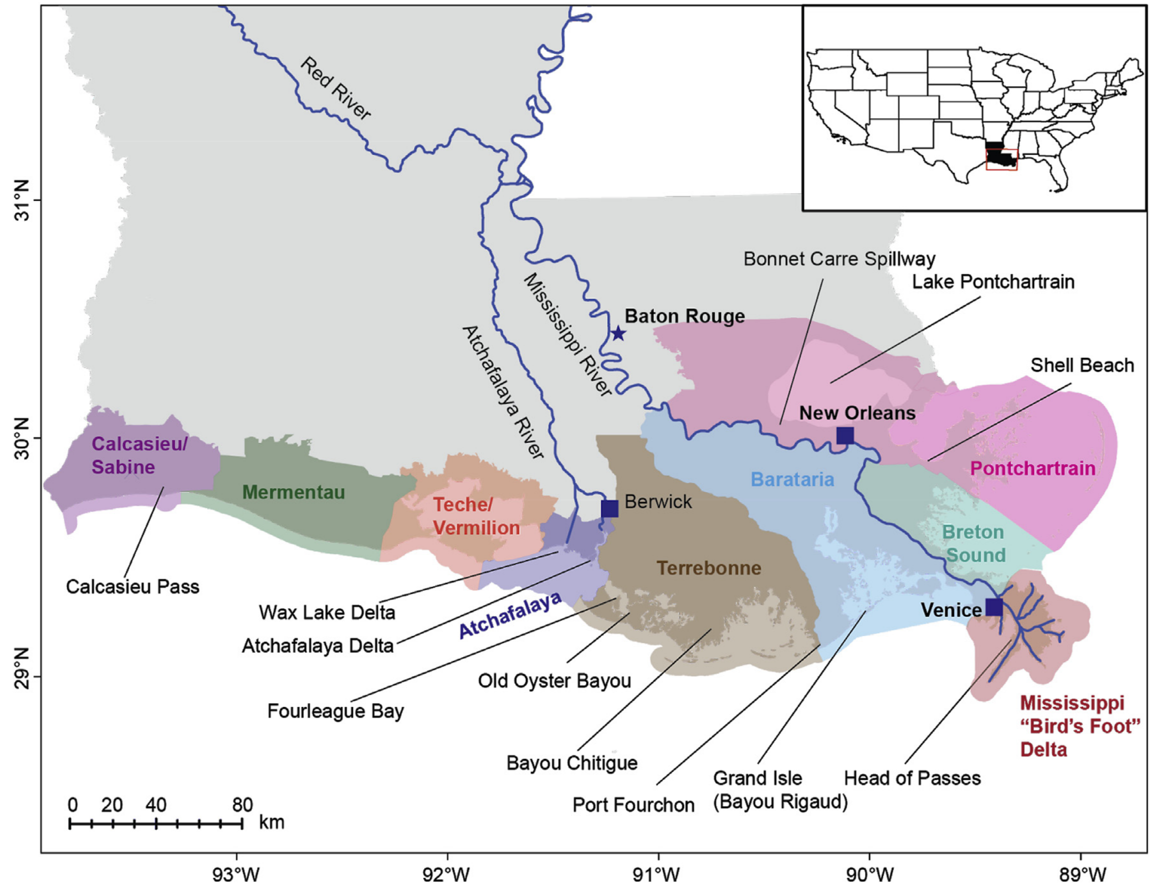

Fig. 1. Map of coastal Louisiana highlighting features and locations relevant to this review. The highlighted regions are hydrological basins designated by Louisiana Coastal Protection and Restoration Authority (CPRA) for the Coastal Master Plan (basin GIS data available at https://cims.coastal.louisiana.gov/).

variability in the context of coastal restoration.

Coastal water level variability depends on the interplay among a suite of natural environmental and human activities. Major environmental drivers are river discharge, tidal fluctuations, wind waves, atmospheric factors like storms, topography, and sea-level changes while anthropogenic activities such as levees, canal construction, dredging, subsurface fluid extraction, diversions, and flood control impoundments, among others, can all affect water level dynamics along the coast. While these general processes are relevant to systems around the globe, disentangling the water level signals and attributing them to the multitude of factors previously mentioned is a local exercise. Thus, we focus our review on the MRD in coastal Louisiana, but the general concepts discussed in this manuscript are applicable to coastal systems globally.

A holistic understanding of the processes affecting water levels in Louisiana is especially pertinent to restoration efforts aimed to abate one of the most drastic examples of coastal vulnerability in the world. The implementation of the Louisiana Coastal Master Plan (CPRA, 2017) functions as type of grand experiment combining scientific research, engineering, management, and monitoring that demonstrates the complexities involved with large-scale restoration efforts. The issues associated with the MRD are not unique; many large and heavily-populated deltaic regions around the world face their own issues with rising sea levels, high rates of subsidence, and human-altered hydrology and sediment transport (e.g., the Yellow and Nile river deltas; Syvitski et al., 2009; Renaud et al., 2013; Day et al., 2016a,b,c). The lessons learned from research and restoration efforts in Louisiana have the potential to impact management policies worldwide.

2. Climate of coastal Louisiana

Atmospheric processes are important drivers of water level variation and flux along Louisiana's coast and the general regional climate plays a central role in determining the impact of these processes. Meteorological events, ranging from slight temperature changes and breezes to more substantial rain events, to air mass thunderstorms and the passage of mid-latitude wave cyclones with their attendant fronts, to tropical disturbances, to the most intense Category 5 hurricanes, all play a role in shaping the coastal landscape. The long-term pattern of such weather phenomena, including their means, frequencies, variability, and extremes, characterize the climatic input on Louisiana's coast.

Climatological forcing is exacerbated by the low-lying and low-relief terrain associated with a coastal deltaic landscape (Yodis and Colten, 2012). The microtidal range in the northern Gulf of Mexico might seem at first to buffer the impacts of weather and climate, but instead it ensures that atmospheric forcing permeates throughout the water column and across the whole delta (Roberts et al., 1989; Vega et al., 2013). Moreover, the gradual changes and fluctuations in hemispheric-to-global-scale atmospheric forcing patterns, such as changes in eustatic sea level, leave Louisiana's coastal zone in a precarious situation regarding the preservation and restoration of coastal ecosystems.

Like all other places, the most fundamental control on climatic conditions in coastal Louisiana is the broad-scale location (Reynolds et al., 2018). The subtropical latitude and proximity to the Gulf of Mexico ensure that warm, humid conditions persist for most of the year, punctuated by short, interrupted cool periods from October to April, and an occasional Arctic outbreak (Mortimer et al., 1986). But the Gulf of Mexico moderates the climate, such that temperatures (both means and extremes) are a few degrees cooler in summer, despite the lower latitude, and far milder in winter, than those found in northern Louisiana (Vega et al., 2013).

Mean annual temperature is about 20 °C, with daily average highs ranging approximately 19 °C in January to 32 °C in July, and daily minima averaging about 7 °C and 22 °C in January and July, respectively. Both freezes and temperatures exceeding 38 °C are rare but can occur in the coastal area. Freezes, especially the prolonged and severe types, are expected to become less frequent over time, while extreme heat (defined as a day with a maximum temperature of 35 °C or above) may increase by as much as 20 days per year by 2050 (Osland et al., 2016; Vose et al., 2017).

The state of Louisiana experiences heavy precipitation throughout the year, second only to Hawaii, and typical annual precipitation in coastal Louisiana is about 140–160 cm (Keim et al., 1995). Annual precipitation averages generally decrease from southeast to northwest across the state and annual totals have ranged from 90 to 220 cm in the coastal regions (Keim et al., 1995). While coastal Louisiana typically experiences somewhat more precipitation during the summer months due to afternoon convective showers (Keim et al., 1995), long term averages indicate that rainfall is rather uniformly spread throughout the year for the whole state (NOAA Climate Normals). However, seasonal extremes have ranged significantly since 1914 (Sklar, 1983). According to Faiers et al. (1997), the 100-year return period for a rainfall event is approximately 200–280 mm for a three-hour duration, 230–300 mm for six-hour duration, 280–360 mm for 12-h duration, and 300–410 mm for 24-h duration. In August 2016, a stationary low-pressure system over an area slightly inland from coastal Louisiana brought unprecedented precipitation of over 750 mm during a five-day period, which caused catastrophic flooding in 21 Louisiana parishes, billions of dollars in property damages, and 20,000 evacuations (Wang et al., 2016; van der Wiel et al., 2017).

A climatic water balance based on Thornthwaite (1948) for Hammond, Louisiana (New Orleans International Airport), illustrates seasonal patterns of precipitation, evaporation, and surplus (Fig. 2). While long-term averages suggest that rainfall is rather consistent throughout the year (NOAA Climate Normal), Lane et al. (2016) observed highly variable monthly precipitation at New Orleans International Airport from 2004 to 2014 (Fig. 2, left). As typical of coastal Louisiana, more rain was observed in the later summer months before the monthly rainfall total decreased in the autumn months (Fig. 2, right). Potential evapotranspiration (PET) followed a similar trend, but low values of PET were also observed throughout the winter (Fig. 2, right). Runoff from rainfall typically occurs during each month of the year in coastal Louisiana (Keim et al., 1995), and the data from New Orleans airport indicates that rainfall is in excess of PET for the majority of the time (Lane et al., 2016), with June, August, and September being the exceptions from 2004 to 2014 (Fig. 2, left). Accordingly, the average annual precipitation was 1531 mm and the average annual PET was 1074 mm, which results in a net water surplus of 450 mm/yr (Lane et al., 2016). The greatest water surplus occurs during the winter months, since PET is very low.

The quasi-permanent Bermuda-Azores high-pressure system in the subtropical north Atlantic Ocean exerts an important influence on weather and climate of coastal Louisiana year-round (Davis et al., 1997). In summer, it tends to be strengthened and displaced northward (Li et al., 2015). This position allows its "clockwise and outward" flow to advect warm, humid air from the Gulf of Mexico into the interior of the U.S., with Louisiana experiencing light, southerly flow of humid air on most days (Rohli et al., 2004). In winter, the Bermuda-Azores high is weakened and displaced southward. Therefore, which makes its clockwise and outward flow is less effective in advecting humid Gulf air inland (Davis et al., 1997)., and instead, extratropical, west-to-east-traveling mid-latitude low pressure systems (cyclones) and their attendant fronts exert a more important impact on Louisiana's coastal weather during the cooler half of the year (Hardy and Henderson, 2003; Feng and Li, 2010). Near-surface local winds result from the position relative to the low-pressure core, and therefore, counter-clockwise rotating winds near the center of the mid-latitude wave cyclone. Thus, as the low-pressure center migrates from northwest to north to northeast of coastal Louisiana, the typical response of local surface winds is a veering from southerly to southwesterly to northwesterly. This parade of mid-latitude wave cyclones or frontal systems, occurring 30 to 40 times per year between the months of October and April (Walker and Hammack, 2000), causes winds to be variable in direction along Louisiana's coast during the cool half of the year. Occasionally in winter, mid-latitude wave cyclones can spin up near the warm/cold boundary of the Texas/Louisiana continental shelf, with the low-pressure center itself tracking over or near coastal Louisiana. These can be vigorous weather- and wave-producers and, because they form quickly near Louisiana's coast, they can be difficult to anticipate.

The Louisiana coast is also vulnerable to the effects of tropical cyclones, ranging in strength from weak tropical waves up to the most intense (Category 5) hurricanes. These are most common in August and September but can occur from late May into November. Such storms can generate flooding and drastically affect normal hydrologic regimes (Day et al., 1977, 2007; Conner et al., 1989; Cahoon et al., 1995; Rybczyk et al., 1995), in addition to causing potentially billions of dollars in damages. According to Vega et al. (2013), billion-dollar weather events affecting Louisiana this century include Tropical Storms Allison (2001; $5.1 billion) and Lee (2011; $1.6 billion), and Hurricanes Ivan (2004; $13 billion), Katrina (2005; $134 billion), Rita (2005; $16 billion), Ike (2008; $27 billion). The 2016 flood also likely caused similar levels of damage (Wang et al., 2016; van der Wiel et al., 2017).

3. Factors influencing water levels

3.1. River flow

As with many environmental processes in Louisiana, water level variability along the coast is related to the dynamics of the Mississippi River. The influence of the river discharge on coastal water levels depends on the hydrological connectivity between the measurement site and the river, as well as the strength of riverine input relative to other forcings. Much of the Lower Mississippi River is completely flanked by levees, which prevents overbank flooding and crevasse formation (Day et al., 2016a,b,c). Accordingly, the water that would be distributed over

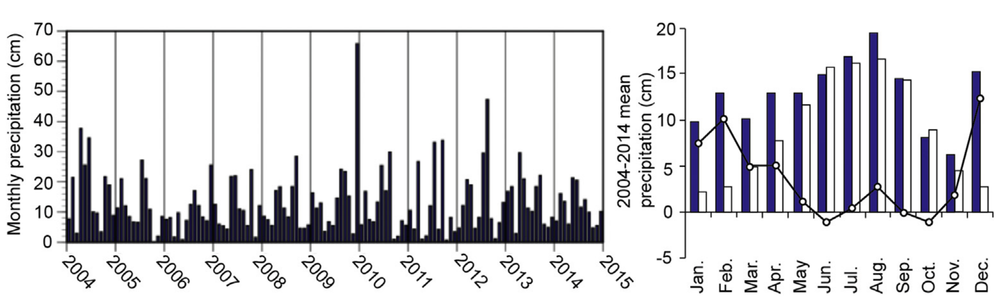

Fig. 2. Monthly precipitation (left panel) and average rainfall (right panel, blue), potential evapotranspiration (right panel, white) and net surplus/deficit (right panel, line) at the New Orleans International Airport from 2004 to 2014 (modified from Lane et al., 2016). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

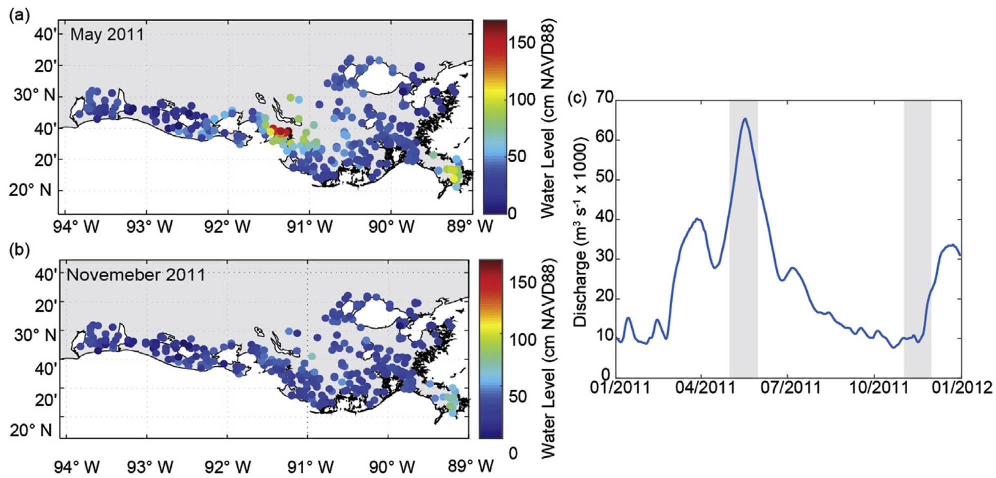

Fig. 3. Mean monthly water level during May (a) and November (b), 2011, at 294 CRMS stations. (c) Mississippi River discharge at Vicksburg, MS (USGS 07289000) during 2011. The shaded boxes denote the averaging period for the water levels depicted on the left panels.

large areas of deltaic floodplain under natural circumstances is localized within the main river channel, causing about two-thirds of the flow to be discharged into the Gulf of Mexico at or slightly north of the Bird's Foot delta (Day et al., 2007). The remaining one-third flows through the Atchafalaya River and into shallow water areas within the deltaic plain.

The placement of levees along the Mississippi River has largely diminished the connectivity between the river and its adjacent wetlands on the delta plain, as shown by comparing mean monthly water levels from the Coastwide Reference Monitoring System (CRMS; data available at https://lacoast.gov/crms2/) database across the Louisiana coast during a record river flood event (May 2011; Fig. 3a) with those during base flow conditions (November 2011; see Fig. 3b). Wetlands flanking the leveed mainstem Mississippi River remain largely unchanged by changes in river discharge. Conversely, during base flow conditions, water levels are less than 40 cm NAVD throughout coastal Louisiana, except at the mouth of the river where they are slightly elevated. During flood conditions, water levels are elevated by up to 100 cm above their base flow conditions in wetlands flanking the lower Atchafalaya River and Wax Lake outlets (red dots in Fig. 3a), which are both Mississippi River distributaries that lack levees (Day et al., 2000).

Water levels in coastal Louisiana are influenced by the Mississippi River discharge, with clear spatial and temporal heterogeneity (Fig. 3). Increased water levels due to river flooding can lead to levee overtopping and cause damage to surrounding communities. In more typical and benign conditions, river flow acts in tandem with basin processes to regulate water levels in coastal Louisiana. Sites near the Wax Lake/Atchafalaya Deltas are strongly impacted by the river changes (i.e., the fluctuations in Atchafalaya River discharge are largely controlled by the Mississippi River; see Fig. 3), and the increased water surface elevations in this region are likely due to freshwater capture by the more constricted Gulf Intracoastal Water Way, and the magnitude of increase is generally related to the duration of high stage in the Wax Lake outlet (Swarzenski, 2003). The relationship between river discharge and water levels at the delta head (Bird's Foot) is less stark than in the Atchafalaya region, which is likely due to the lack of lateral constraints on the flow, which allows water to spread readily over the shelf edge. Nearly half of the discharge exits the main river channel via both man-made and natural lateral outlets in the lower 75 km of the river before Head of Passes (HOP) south of Venice, LA (Allison et al., 2012; Kolker et al., 2018), compared to roughly 10 km of lateral outflow in Wax Lake delta in the Atchafalaya Bay (Hiatt and Passalacqua, 2015, 2017). Gradual loss of discharge from the main river channel, plume spreading, and backwater effects work to diminish the influence of discharge fluctuations at a river mouth (Nittrouer et al., 2011, 2012; Lamb et al., 2012; Hiatt and Passalacqua, 2017; Esposito, 2017).

Floods and high-discharge events are obvious drivers of increased water levels in rivers and can cause inundation of the surrounding floodplains, in addition to flooding cities and towns. Water levels in the lower Mississippi River can change more than 10 m between recent high and low flows (Allison and Meselhe, 2010, Fig. 4a). Changes in river water levels as a function of discharge can be understood for confined channels using open-channel hydraulics theory (Chow, 1959; Henderson, 1966). Flow conditions in coastal deltaic regions like

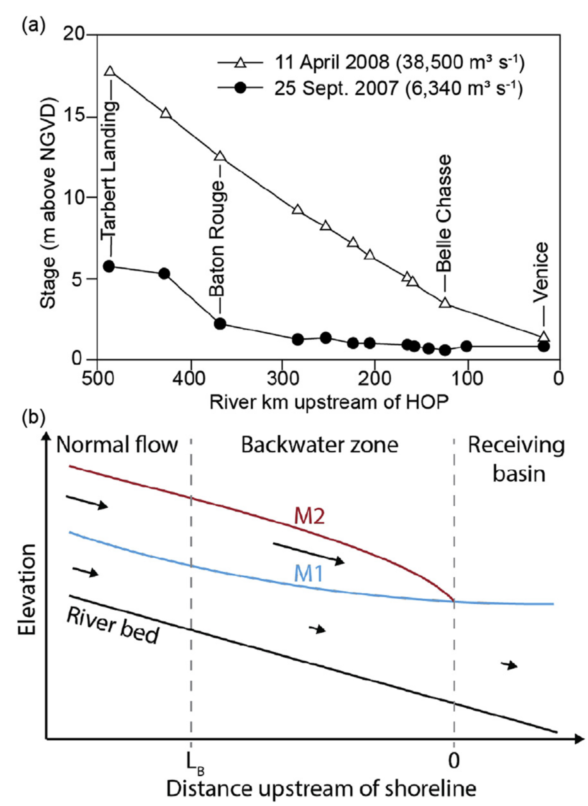

Fig. 4. (a) Water surface elevations for the lower Mississippi River upstream of Head of Passes (HOP) during a low-flow event on 25 September 2007 (black circles) and a high-flow event on 11 April 2008 (white triangles). Figure is reproduced from Allison and Meselhe (2010). (b) Schematic of two types of water surface profiles for subcritical flows in mildly-sloping channels modeled after the schematic presented by Lamb et al. (2012).

Louisiana are generally subcritical (*Froude number* < 1) and the water surface elevation of the receiving basin has an influence on the hydraulics in the river channel well upstream of the receiving basin – a phenomenon known as the backwater effect. Water levels in a mildly-sloped channel with subcritical flows are determined by the channel geometry, slope, discharge, and the water surface elevation of the receiving basin. These parameters determine the normal depth of the river flow, or the depth at which gravitational forces are balanced by frictional forces. The water surface elevation at the coastline relative to the normal depth in the channel determines the shape of the water surface elevation profile in the channel. When the water level at the coast is at a higher elevation than the normal depth in the channel, the channel water surface elevations generally follow an M1 curve, a decreasing concave up profile in the downstream direction (Fig. 4b). When discharge in the channel is high and the normal depth in the channel is at a higher elevation than the water surface at the coast, a concave down, decreasing water surface profile known as an M2 curve is observed (Fig. 4b). However, even under very high discharge conditions (> = 40,000 m3/s), the Lower Mississippi River still maintains an M1 profile (e.g., Nittrouer et al., 2012), although the water surface slope is much greater than at lower discharges. This leads to higher velocities and potential flooding in the low-relief coastal region.

While high river discharges can have significant influences on water levels upstream, changes in river discharge often have a limited effect on water levels at a river mouth (e.g., Lamb et al., 2012; water levels at Venice, LA in Fig. 4a), due to lateral spreading of the flow in the receiving basin. For example, Karadogan et al. (2009) used a high-resolution two-dimensional hydrodynamic model of the MRD from near New Orleans (at Carrollton, LA) to the Bird's Foot delta beyond the HOP to study the influence of river discharge, sea level rise, and tidal variability on the MRD hydraulics. The high discharge case produced water levels that were nearly 3 m higher at Carrollton (165 km upstream of HOP) than the low flow case. Karadogan et al. (2009) also reported that upstream water levels associated with high and medium discharges were not affected by basin water level changes, but the basin water level variability significantly affected water levels throughout the domain for the low flow case. With a simplified quasi two-dimensional model of the MRD, Lamb et al. (2012) quantified the effect of lateral spreading on water surface elevations and depositional/erosional processes. They found that the main control on water levels in the backwater zone is the degree of lateral spreading allowed at the coast. Very high discharges produced water levels that were up to 20 m higher than low flow periods near the coast when lateral outflow was limited (Lamb et al., 2012). In a similar effort using a schematized channel-wetland topography, Hiatt and Passalacqua (2017) showed that the gradual transition between confined river flow and laterally-unconfined flow through a deltaic system where roughly 50% of the river discharge is laterally transported to adjacent floodplains leads to significantly lower water levels throughout the backwater zone as compared to a confined case.

While the notion of overbank flooding may seem obvious for relatively high flows, Hiatt and Passalacqua (2015; 2017) show that lateral outflow from deltaic channels exists during relatively low flow conditions. Similarly, Esposito (2017) shows that discharge fractions lost in two distributary crevasse splays are in many cases enhanced by decreases in total riverine discharge, which is attributed to water level modulation by base level and lateral spreading. Higher fractions of discharge lost resulted in higher surface water slopes (Esposito, 2017), which suggest a positive feedback exists between lateral outflow and surface water slope. Interestingly, discharge loss through lateral outflow appears to have significant control on distributary channel stability (Esposito, 2017), sediment transport (Shaw et al., 2016), and nutrient dynamics (Hiatt et al., 2018). In all cases, lateral outflow from the river channel decreases water level in the river channel. This established phenomenon of open-channel hydraulics (Chow, 1959; Henderson, 1966) has important implications for the flooding risk, depositional patterns, and water quality issues associated with river and sediment diversions.

Releases of freshwater through Mississippi River diversions can induce widespread wetland inundation in the marshes of their receiving basins. In the marshes of upper Breton Sound, water levels increased by nearly 45 cm in response to a 14-day, 185 m^3s^{-1} release through the Caernarvon diversion (Lane et al., 2007) at a location 7 km from the diversion structure (Snedden et al., 2007a; see Day et al. (2019) in this issue for further detail on the Caernarvon diversion). Coincident with these releases and elevated water levels were periods during which roughly half the volume of diverted river water was estimated (through a mass balance approach) to have overflowed out of conveyance channels and flow down basin over the marsh surface as sheet flow (Snedden et al., 2007b). This sheet flow, which was typically induced when diversion inflows exceeded roughly 115 $m^3\,s^{-1}$, inundated the wetlands in the region with sediment-rich (~100 mg/L) river water and has been linked to elevated short-term vertical accretion rates (Wheelock, 2003). However, sheet flow of river water over 57 km^2 of the marsh is not the only mechanism for delivering sediments to wetlands (Snedden et al., 2007b), as sediments that are not delivered to marsh platforms by fluvial inputs can be stored in adjacent lakes and bays where subsequent winter storms resuspend and transport sediments from lakes to marsh platforms (Reed, 1989). Furthermore, such sheet flow increases inundation time and thus can stress emergent plants, which produce the peat that controls marsh vertical accretion in marshes of the MRD plain (Nyman et al., 2006), throughout the Gulf coast (Callaway et al., 1997), and on the Atlantic coast (Neubauer, 2008).

3.2. Tides

The Gulf of Mexico coastal region has a complicated tidal regime. The coastal waters of Louisiana are microtidal (less than 2 m), but tidal ranges can vary considerably throughout the MRD (CRMS data). While much of the inland MRD has average tidal ranges that are less than 10 cm, tidal ranges can approach 60 cm in the central regions of the Louisiana coastline (Fig. 5). The largest tidal ranges in the coastal region (> 35 cm) are typically found in the Vermilion-Atchafalaya Bay complex and in the westernmost portion of the Terrebonne Basin (Fig. 5). At Bayou Rigaud at Grand Isle, the mean tidal range was 32 cm for 1951–1970 (Baumann, 1987), which is fairly typical of current tidal ranges along the central and eastern portions of the Louisiana coast (Fig. 5). However, large expanses of the region exhibit greatly reduced tidal ranges (< 10 cm), owing to diminished estuary-ocean exchange brought about by frictional attenuation in the inland reaches of the delta plain or by the presence of water control structures in the heavily impounded Chenier Plain (Fig. 5).

The lunar tide in the region is mainly diurnal, with the O_1 and K_1 constituents being its primary components. The importance of semi-diurnal constituents (e.g., M_2, S_2) in the overall astronomical tidal fluctuations along the northern and eastern coasts of the Gulf of Mexico is minimal. One important implication of the dominance of the diurnal constituents in this region is that the fortnightly cycle in tidal amplitude results from an offset of the plane of the moon's orbit relative to Earth's equator. This 13.6-day tropic-equatorial cycle is physically distinct from the 14.8-day spring-neap fortnightly cycle in tidal amplitude that occurs in semi-diurnal regimes as a result of varying positions of the sun and the moon relative to Earth. Though coastal tides in the region transition to a mixed regime toward western Louisiana and eastern Texas (Flick et al., 2003, Fig. 6), this transition is not evident in the coastal marshes of southwestern Louisiana due to the continuous beaches and cheniers [see Kirby (2002) for definitions] that run parallel the coast in addition to the highly impounded nature of the region. Fig. 6 depicts typical tidally-regulated water levels at four NOAA Tides and Currents Monitoring Stations along the Louisiana coast for June and July 2017.

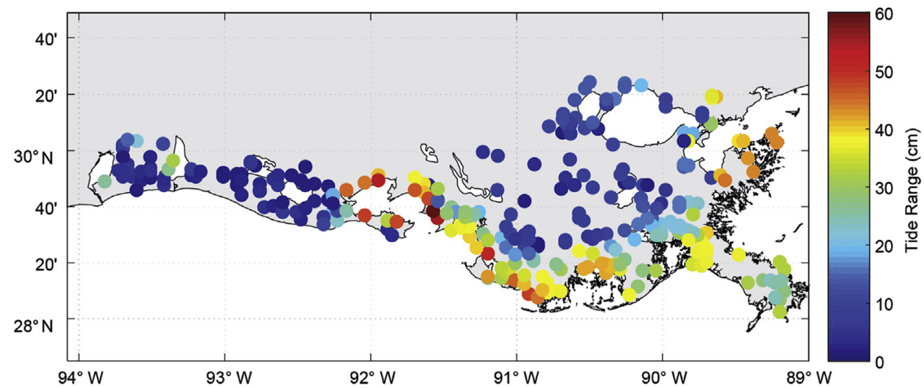

Fig. 5. Tidal ranges calculated as average differences in height between consecutive high and low waters over a tidal cycle, generated at 294 CRMS stations (www.lacoast.gov/crms2/), 2010–2017.

Maximum tidal ranges are generally observed near the summer and winter solstices, and the minimum tidal ranges are measured during vernal and autumnal equinoxes (Baumann, 1987). The tropic-equatorial (bi-weekly) tidal cycles can alter the tidal ranges significantly, a common feature of systems dominated by diurnal tides (Marmer, 1954). Average tidal ranges in the Atchafalaya Bay area are 35–40 cm (Shaw and Mohrig, 2014; Sendrowski and Passalacqua, 2017), but water level ranges during tropic tides approach 1 m. The strongly diurnal tide at Lake Pontchartrain has a very low tidal range of 11–15 cm (Outlaw, 1982; Swenson and Chuang, 1983; NOAA, 2014). Baumann (1987) calculated that tropic tides increased tidal range by about 45%, while equatorial tides had a range of about 45% below average at Bayou Rigaud. Since tidal ranges are small in Louisiana, tidal variability only controls Mississippi River stages in the backwater zone at very low discharges, but at average and high discharges the effect of tides becomes less important (Karadogan et al., 2009). However, the Mississippi River is one of the largest in the world, whereas planned river (or sediment) diversions will carry discharges that are potentially orders of magnitude smaller than those observed in the Mississippi River and are not laterally-restricted by levees. Thus, tides may play an

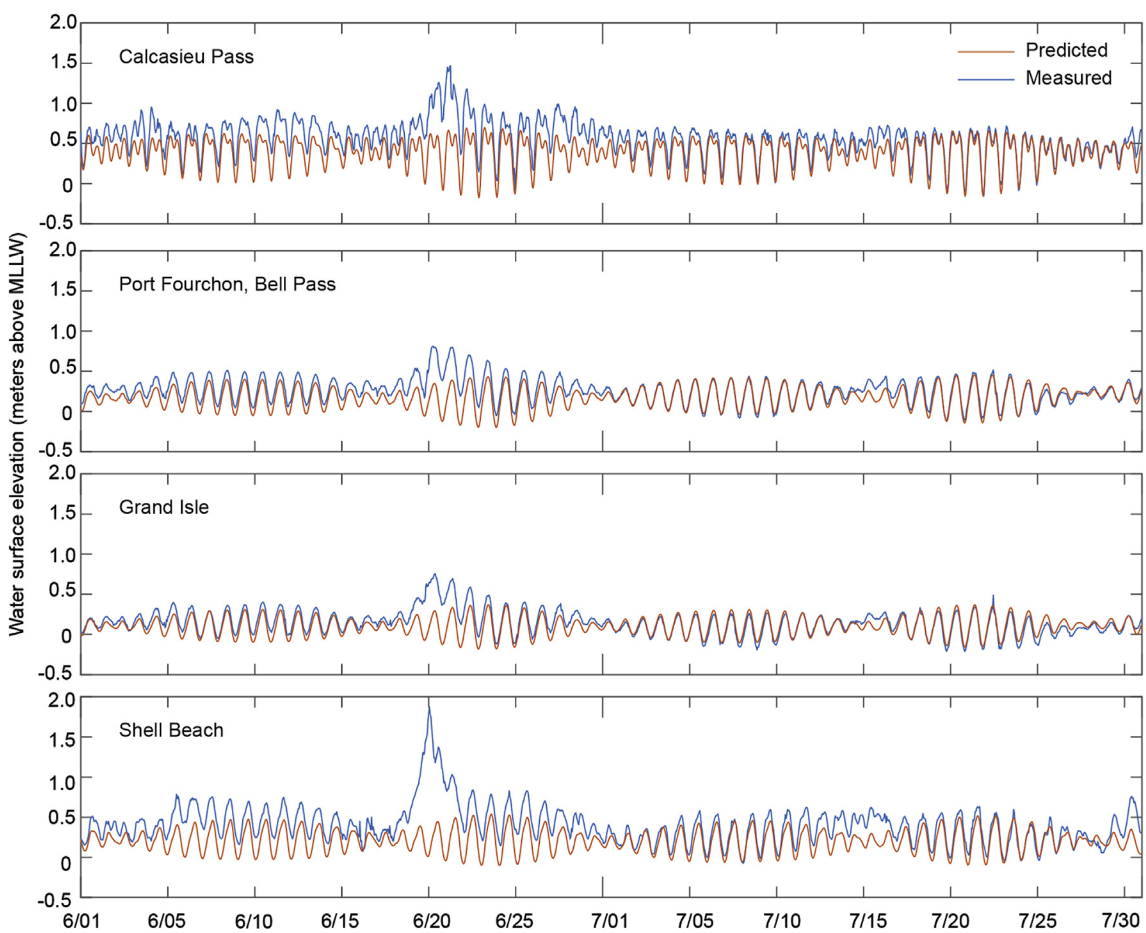

Fig. 6. Summary of measured and predicted water level at four NOAA Tides and Currents stations along the Louisiana coast for June and July 2017. Tidal ranges were generally less than 50 cm. Tides are mixed in western Louisiana and are strongly diurnal in the eastern portions of the state. A low-pressure system with wind speeds exceeding 10 m/s crossed the region on 20–22 June 2017 and caused water level setup. The data are from stations 8768094, 8762075, 8761724, and 8761305 and are freely available at https://tidesandcurrents.noaa.gov/.

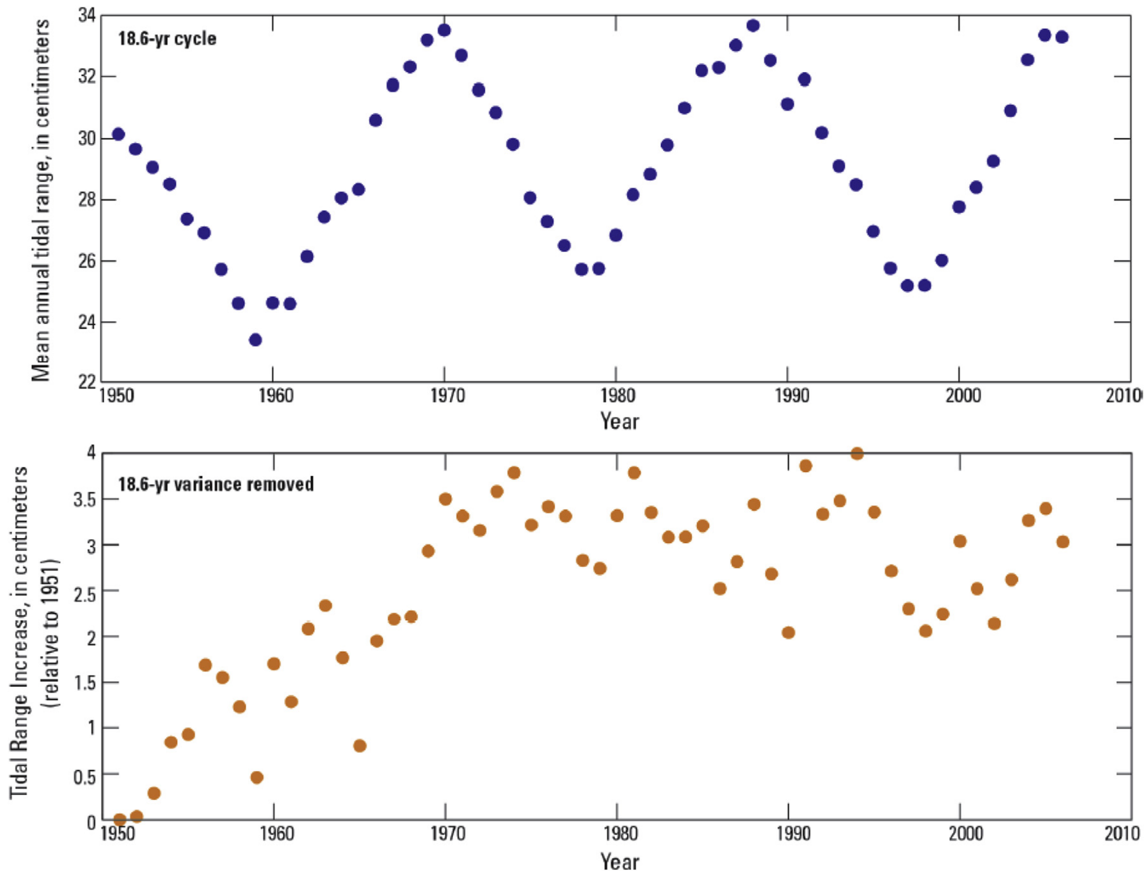

Figure 7. (top) 18.6-yr tidal range cycle at Bayou Rigaud (NOAA ID: 8761720) and Grand Isle station (876172) in Barataria Basin, LA. (bottom) The residual signal in water levels after removing the 18.6-yr signal (graph from Kindinger et al. (2013) based partly on data from Howes (2009)).

important role in regulating water levels and the morphological evolution of the restoration sites.

The declination of the moon's orbit with respect to Earth's equator modulates an 18.6-year cycle in tidal amplitude (McKinnell and Crawford, 2007) and regional sea level (Baart et al., 2012). The alignment of the sun and the moon directly over Earth's equator can increase tidal ranges. Diurnal tides are primarily influenced by this cycle and exhibit their maximum range every 18.6 years (Marmer, 1954). The 18.6-year lunar nodal cycle affects tides worldwide and can contribute to occurrence of extreme sea levels (Gratiot et al., 2008; Haigh et al., 2011). While this tidal variation is often ignored in tidal fluctuation analysis due to the necessity for long-term water level records, Baumann (1987) first quantified its effects at Bayou Rigaud from 1950 to 1980 and recent efforts of FitzGerald et al. (2008), Howes (2009), and Kindinger et al. (2013) have extended this analysis into the present. The 18.6-year tidal cycle causes a tidal range variation of about 10 cm from the long-term average (Fig. 7). Baumann (1987) suggests that percent time inundation is more strongly related to high-frequency variability in water level than due to the 18.6-year cycle. Additionally, the water level anomaly associated with the 18.6-year tidal cycle is much less than the variability induced by the tropic-equatorial biweekly tidal cycle (e.g., Fig. 6).

3.3. Atmospheric forcing

3.3.1. Cold fronts

In microtidal areas such as the northern Gulf of Mexico, climatological forcings often have more of an influence on water levels than astronomical tides (Childers and Day, 1990; Georgiou et al., 2005). Wind influence on estuarine water levels and marsh-bay and bay-shelf exchange is important in coastal Louisiana because it can regulate marsh sediment fluxes and accretion (Childers and Day, 1990; Perez et al., 2000), as well as marsh degradation via wave edge erosion (Day et al., 2011; Mariotti, 2016; Ortiz et al., 2017). This is particularly true during autumn and winter, when the passage of 12–24 h winter storm systems occurs about every 4–7 days (Chuang and Wiseman, 1983; Roberts et al., 1989, 2015; Moeller et al., 1993; Mossa and Roberts, 1990; Li et al., 2011) and this storm-induced wind stress causes shelf sea levels to fluctuate with typical amplitudes of 50 cm or more.

Along- and cross-shore wind stress have been observed to be important drivers of subtidal water-level variability in Louisiana estuaries, in both observational (Snedden et al., 2007a,b; Snedden, 2016) and analytical (Feng and Li, 2010) studies, and the importance of cross-shore winds increases westward along the Louisiana coast owing to a corresponding increase in shelf width, which diminishes the importance of Ekman transport through increased bottom friction effect (Chuang and Wiseman, 1983). Water level set-ups and draw-downs due to cold front passages are due to local wind stress, wave setup and atmospheric pressure changes (Li et al., 2011). Cold fronts can be eastward-migrating (oblique) or move from north to south (parallel), depending on the origin and evolution of the air masses involved (Georgiou et al., 2005). Prior to a typical frontal passage (Georgiou et al., 2005), southerly and easterly winds cause an onshore encroachment of Gulf water along the Louisiana coast, inducing a net influx of water into coastal bays and surrounding wetlands which can be inundated with 30–50 cm of water during this pre-frontal phase (Denes and Caffrey, 1988; Childers and Day, 1990). As the low-pressure front passes, winds shift to westerly and then northerly and water rapidly drains from the shallow wetlands and bay. This frequent and energetic inundation and draining is a major transport mechanism for sediment, nutrients, and organic matter among coastal bays and adjacent wetlands and the Gulf of Mexico (Madden et al., 1988; Childers and Day, 1990; Stern et al.,

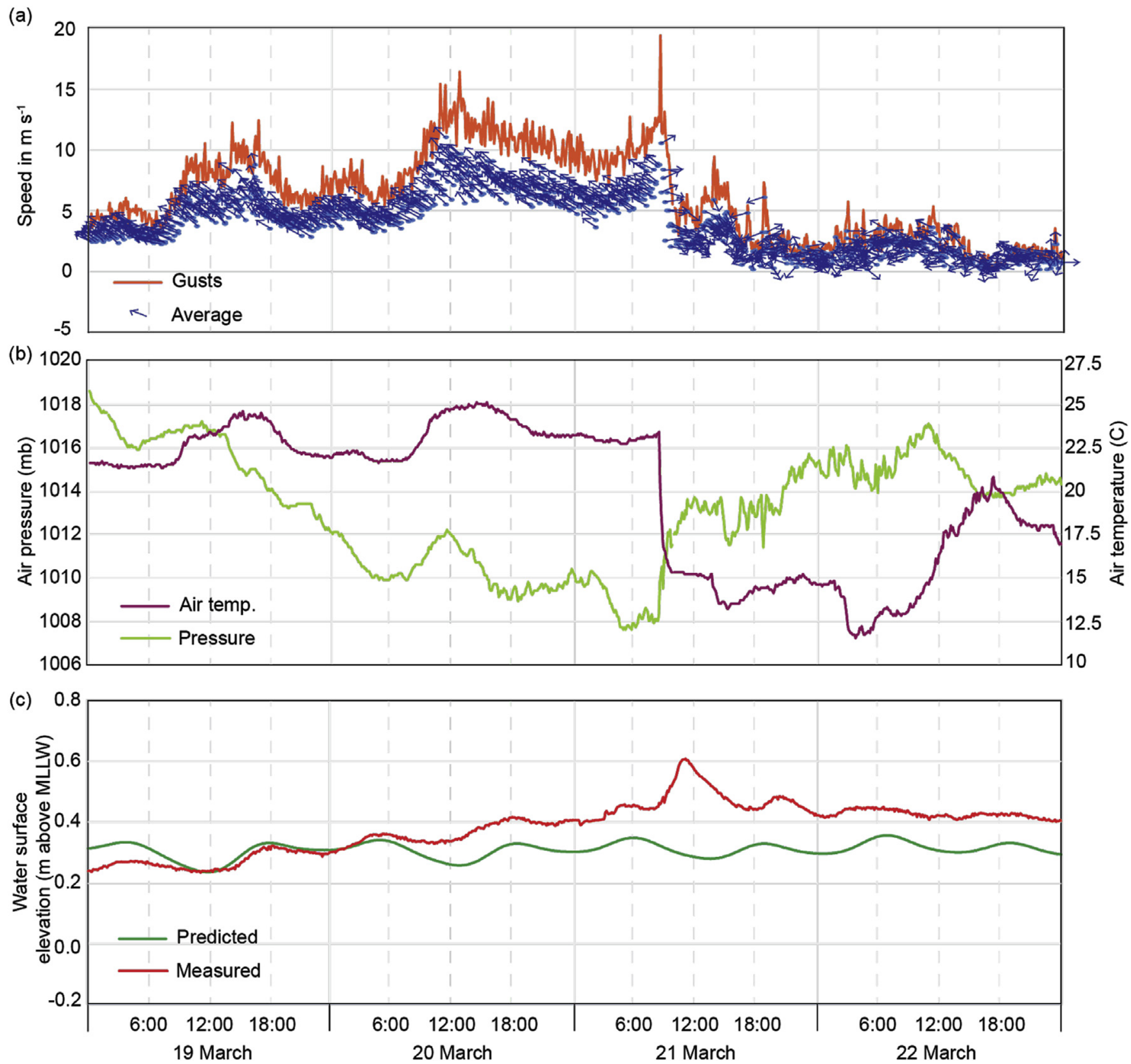

Fig. 8. Summary of hydrological and meteorological variables during the passage of a cold front at NOAA Station No. 8764044, Berwick, Louisiana in 2012. During the cold front passage on 21 March 2012, the wind speed and direction (blue arrows) shift, air temperature decreases, and barometric pressure increases from a pre-frontal period of low pressure, causing a spike in measured water levels (modified from Roberts et al., 2015). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

1991; Perez et al., 2000). These typical patterns are illustrated for a NOAA monitoring station located in Berwick, Louisiana (Roberts et al., 2015, Fig. 8).

Water level fluctuations during cold fronts can be substantial, often exceeding the astronomical tidal range of the northern Gulf coast by a factor of three or four (Murray, 1975), though the amplitude of these meteorologically-induced fluctuations has been observed to be strongly dissipated by friction as they propagate inland through vegetated marsh landscapes with shallow average depths (Snedden et al., 2007a,b). Kemp et al. (1980) recorded meteorologically-induced water level ranges exceeding 1 m during the winter months associated with frequent frontal passages, nearly double the average astronomical tidal range along the northern Gulf Coast. Perez et al. (2000) reported that Fourleague Bay water levels vary by as much as 0.80 m over the course of a frontal passage. In Caminada Bay, LA, Kjerfve (1973) reported that water levels and circulation were controlled by winds on a scale of a few days and diurnal tides on a daily scale. Following a strong frontal passage, Perez et al. (2000) calculated that 56% of the volume of Fourleague Bay was exported to the Gulf in one day, and Swenson and Chuang (1983) determined that frontal passages could induce volume fluxes up to six times greater than the tidal prism in Lake Pontchartrain. Similarly, Feng and Li (2010) observed cold fronts to flush more than 40% of Louisiana coastal bay waters out onto the continental shelf in under 40 h. Cold fronts can also induce saltwater intrusion into primarily freshwater bays (Li et al., 2011).

Wind events can act to modulate inundation throughout different landscape elements in coastal deltas (Geleynse et al., 2015; Sendrowski and Passalacqua, 2017). In Wax Lake delta, for example, inundation from both fluvial and marine sources caused nonuniform and nonlinear fluctuations in inundation ranging from 10 to 65% of the ~100 km^2 Wax Lake delta plain from 2006 to 2011 (Geleynse et al., 2015). In a deltaic island at Wax Lake delta, daily wind events modulate marsh water levels by up to 1 m (O'Connor and Moffett, 2015), which cause significant inundation of the island with mild topographic relief (~0.5 m) and modulate transport timescales (Hiatt and Passalacqua, 2015). Geleynse et al. (2015) ran hydrodynamic simulations, assessed an analytical long-wave model, and measured wind velocities to determine that wind stress and direction were the primary controls on inundation degree and pattern at Wax Lake delta, which is in general agreement with other measurements of decimeter-scale water level drawdowns in the region associated with frontal passages from N-NW directions (Walker and Hammack, 2000). However, Geleynse et al. (2015) show that island geometry can also modulate patterns and depth of inundation at Wax Lake delta by forcing both water level setup and drawdown to coexist within the delta plain for a single wind event. Thus, spatial variability in local geometry and wind directionality are important variables to consider when predicting the influence of cold fronts on water level variations.

Spatial variability in water levels induced by river discharge, tides, and atmospheric events gives rise to pressure gradients that facilitate the transport of water and materials entrained in the flow (e.g., sediment, solutes, and organisms). Tidal exchange studies are often used to estimate sediment budgets for estuarine systems, but cold front passage causes major disruptions to tidally-driven sediment transport patterns in the MRD. Several studies have focused on water and material transport in the Fourleague Bay system. Stern et al. (1986, 1991) investigated total suspended sediment (TSS) and nutrient transport in a tidal freshwater bayou near the mouth of the Atchafalaya River. TSS transport was ebb- or seaward-directed for all seasons, but transport was two orders of magnitude greater during high river discharge than during tidally driven conditions. In lower Fourleague Bay, Childers and Day (1990) examined marsh-water column sediment exchanges utilizing throughflow flumes and reported that lower bay marshes were generally a sink for sediment during the high river flow months. Sediment was exported from the marsh, however, during a winter storm, which occurred during low tide. Perez et al. (2000) monitored TSS concentrations in Fourleague Bay as a function of Atchafalaya River discharge and winter frontal passage. Transport of sediments was largely ebb-directed throughout the 89-day study due to the large continuous supply of sediment from the Atchafalaya River. Higher values of TSS up to nearly 2000 mg/l were observed during frontal passage than during quiescent, tidally-driven time periods, suggesting that atmospheric events may modulate sediment export and deposition within the surrounding wetlands.

3.3.2. Multi-decadal water level changes

Multi-decadal fluctuations in mean water level due to atmospheric phenomena may partially explain the historical patterns of wetland inundation and degradation in Louisiana, as well as provide a baseline upon which to evaluate modern inundation and wetland loss patterns. For example, the daily water level data from Grand Isle shows on average a nearly 1 cm/yr rise in water level over the last 60 years (Fig. 9a) due to subsidence and eustatic sea level rise. Subsidence has dominated over the past half century but during coming decades eustatic sea-level rise will become increasingly important due to predicted eustatic sea-level rise acceleration (Meier et al., 2007; Church et al., 2013).

If the water level data at Grand Isle are expressed as annual averages and the long-term rise is removed (detrended), then it is apparent that inter-annual variations in mean water level by up to 10 cm exist and that water levels are above and below the long-term detrended mean for extended periods (Fig. 9b). For example, from 1955 until about 1970 mean annual water levels were below the long-term detrended mean; from the early 1970s to about 1995 water levels were above the mean, and after 1995 water levels were generally below the mean until recently. Data from recent years suggest that water levels may again be trending above the long-term mean. As the system tends back to a higher water level above the long-term detrended mean, wetlands will likely become more submerged. FitzGerald et al. (2007) performed a similar analysis on the Grand Isle gauge for 1947–2006 and found that land loss in Barataria Bay tracks positively with RSLR and wetland drowning has subsequently increased the tidal prism, which exacerbates the wetland loss by enlarging tidal inlets (FitzGerald et al., 2008). Tidal inlet widening may account for up to 30% of the increase in tidal prism, which adds inundation stress to wetlands that are already subject to increasing rates of RSLR (Kindinger et al., 2013). Thus, it is likely that wetland loss patterns of the past half-century were strongly influenced by these patterns of water level excursions due to diminished/increased wetland inundation and tidal inlet contraction/expansion. Wetland loss rates in the 1970s and 1980s were high (Couvillion et al., 2017) at a time when water levels were often 5–10 cm higher that the long-term detrended mean (Fig. 9c). Conversely, after about 1995, land loss rates decreased at a time when mean water levels were often below the long-term detrended mean, sometimes by up to nearly 10 cm

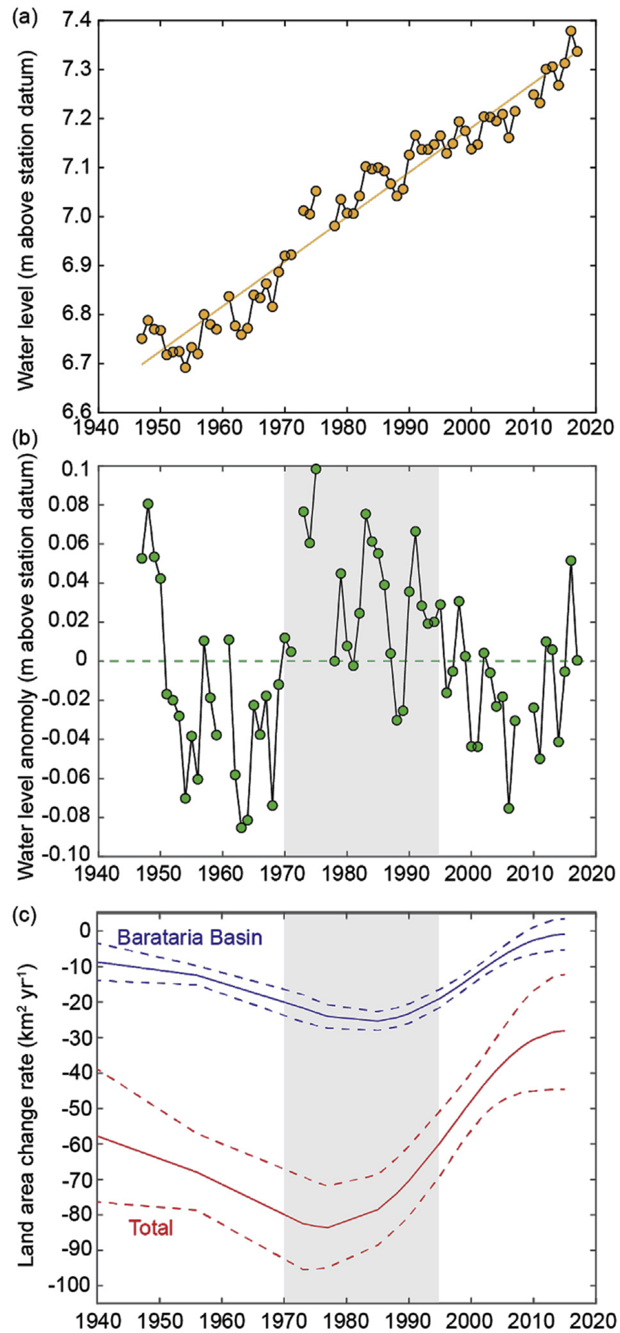

Fig. 9. (a) Annual water level data at NOAA Station No. 8761724 at Grand Isle in the Barataria Basin, Louisiana, from 1947 to 2017. There was a long-term water level increase of about 0.9 cm/yr. Data are freely available from psmsl.org. (b) Annual average detrended water levels at Grand Isle. (c) Land area changes in coastal Louisiana (red) and Barataria Basin (blue) as calculated by Couvillion et al. (2017). The dashed lines represent the 95% confidence bounds for the land area change calculations. Land loss rates increased until reaching their maximum in the 1970s through the 1980s in Barataria Basin (shaded region in b and c) and have steadily decreased since 1990. Since about 1970, changes in coastal land loss rates in Barataria Basin appear to be correlated with the water level anomaly at Grand Isle. A similar trend exists for much of coastal Louisiana. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(Fig. 9b).

These multi-decadal water level changes are likely related to a series of global forcings affecting the Atlantic Basin (Dima and Lohmann, 2007; Kennedy et al., 2007). These include the Atlantic Multidecadal Oscillation (AMO) and the North Atlantic Oscillation (NAO). The AMO refers to the 35–70-year cycle in Atlantic temperatures characterized by 15–40 years of dominantly warmer-than-normal Atlantic temperatures (positive AMO) followed by 15–40 years of dominantly colder-than-normal North Atlantic temperatures (negative AMO), and then back again (Enfield et al., 2001). While debate continues (Sutton et al., 2018) about the extent to which the AMO is forced by anthropogenic activity (e.g., Mann and Emanuel, 2006) vs. natural causes (e.g., Knight et al., 2005), it is likely caused by some combination of both and has many potential atmospheric, marine, and environmental associations (Enfield and Cid-Serrano, 2009).

The NAO refers to variability in atmospheric pressure between two semi-permanent, quasi-stationary circulation systems in the north Atlantic Ocean: the subtropical Bermuda-Azores high and the subpolar Icelandic low. This pattern was originally noted by Sir Gilbert Walker in the 1920s but was re-introduced to the scholarly literature in the late 1970s (van Loon and Rogers, 1978; Rogers and van Loon, 1979). The so-called positive phase of the NAO is characterized by anomalously strong Bermuda-Azores high and a simultaneous anomalously-deep Icelandic low. Such conditions promote an intensified south-north pressure gradient across the mid-latitude north Atlantic Ocean, which steers storms eastward rapidly. Because of the intensified Bermuda-Azores high, a positive NAO also results in strengthened clockwise return flow that promotes elevated water levels in the northern Gulf. By contrast, the negative mode of the NAO is characterized by an anomalously weak Bermuda-Azores high and simultaneously weak Icelandic low. Such conditions promote weaker steering circulation in both the north Atlantic mid-latitudes between these two pressure features and weakened return flow around the Bermuda-Azores high. The anomalously weak return flow provides less accumulation of water in the northern Gulf coastal area.

Because of the low tidal range, coastal marshes in Louisiana have a narrow vertical elevation growth range. Though a negative AMO is “good” in the sense that Atlantic hurricane frequency tends to be suppressed during such periods (presumably due to colder ocean waters), based on our research it appears that a negative AMO tends to correspond to high water levels at Grand Isle (Fig. 9). Thus, during a negative AMO regime, any decreased likelihood of accelerated land loss due to catastrophic events may be offset or even overcompensated by an increased acceleration of land loss due to increased inundation depths, tidal inlet widening, and barrier island degradation (FitzGerald et al., 2008; Kindinger et al., 2013), which are associated with periods of relatively high tidal ranges. For marshes already stressed by low elevation and inundation, adding an additional 5–10 cm of water for several years could stress marshes enough to lead to plant mortality (e.g., Day et al., 2011) and geomorphological change. Shifts in the NAO and the AMO will likely exacerbate future periods of wetland loss, especially with accelerating eustatic sea-level rise. Another air-sea modulator at broad scales that may influence long-term water level variability and wetland loss is the El Niño Southern Oscillation, although it has a limited effect on riverine flows in Louisiana (Sanchez-Rubio et al., 2011) except during extreme occurrences (Muller and Faiers, 1984). However, significant impacts on water level responses due El Niño and La Niña have been observed elsewhere, such as the freshwater delta regions of the Chesapeake Bay (Pasternack and Hinnov, 2003). The apparent feedbacks among multi-decadal water level anomaly and wetland loss (Fig. 9), tidal inlet widening, tidal prism increase, and barrier island erosion (FitzGerald et al., 2007, 2008; Kindinger et al., 2013) highlight the complex interplay of the parameters that must be considered for coastal restoration. Significant consideration should be given to the effects of AMO and NAO when developing restoration strategies, especially in regions since their

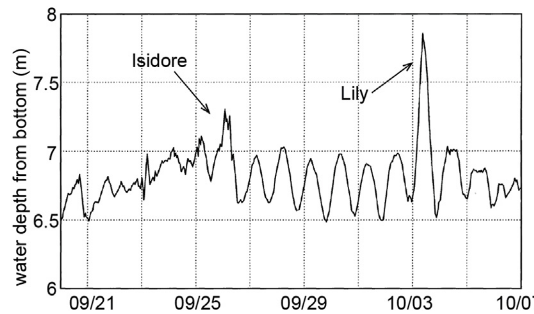

Fig. 10. Impact of Tropical Storm Isidore and Hurricane Lili on water levels at WAVCIS Station CIS 5 (located roughly 16 km southwest of Port Fourchon) during September and October 2002 (modified from Georgiou et al., 2005).

effects on water level and inundation will be pronounced in especially low-gradient systems. For example, river deltas with gradients on the order of 10^{-5} include many of the world's most populated deltas including the MRD, Parana, Amazon, Nile, Lena, Yangtze, Niger, Danube, Huanghe (Yellow River), Pearl, Irrawaddy, and Mekong (Syvitski, 2005). Coupled with increases in RSLR, the next several cycles of relatively high-water level anomalies due to the AMO and NAO compounded with overall RSLR could prove catastrophic for many, especially low-gradient, systems.

3.3.3. Hurricanes and tropical storms

Hurricanes and tropical storms are obvious contributors to abrupt fluctuations in water level (Fig. 10). These are regular, but infrequent, events in Louisiana that typically occur between June and the end of November. The storm surge associated with hurricane winds and pressure differentials can be substantial. The storm surge measurements near New Orleans and the Bird's Foot delta during Hurricane Katrina in 2005 were 2–6 m, but at barrier islands and the coastline east of Katrina's path in Mississippi they were measured at heights up to 10 m above mean sea level (Fritz et al., 2007). On average, both Hurricane Katrina and Rita produced over 3 m of storm surge over hundreds of kilometers of coastline (Day et al., 2007), likely due to the diminished buffering capacity of drowned wetlands in Breton Sound. In 2002, Tropical Storm Isidore and Hurricane Lili produced storm surges of 0.6 and 1.2 m, respectively (Georgiou et al., 2005, Fig. 10). Walker and Hammack (2000) reported that water levels increased by nearly 1 m in the Atchafalaya-Vermilion Bay region due to set-up caused by southeasterly winds associated with Tropical Storm Frances making landfall along the Texas coast in 1998. Conversely, the northeasterly winds associated with Hurricane Georges making landfall in Mississippi in 1998 decreased water levels in the Atchafalaya-Vermilion Bay by as much as 0.65 m over a 3-day period (Walker and Hammack, 2000). The episodic and dramatic increases in water level associated with storm surges in hurricane and tropical storms can cause tremendous damage to coastal communities.

Large storm surges associated with hurricanes have both constructive and destructive effects on wetlands. While hurricanes can result in significant, albeit episodic deposition (Turner et al., 2006), the deposition may be offset by erosion elsewhere, depending on the storm track and associated surge locations. Erosion associated with Katrina and Rita converted about 100 km^2 of wetlands in the Breton Sound Basin to shallow marsh, with some areas mined to more than 1 m deep (Day et al., 2007), while other regions received 5–10 cm of deposition. However, the results of a geochronology study of 27 cores collected in Breton Sound (Smith et al., 2015) indicate that deposition due to hurricanes is an order of magnitude less than the deposition results previously reported for Hurricane Katrina (e.g., Turner et al., 2006). Accordingly, Smith et al. (2015) reported that long-term sediment deposition due to hurricanes is significantly less than what is supplied by fluvial sources, as well as the sediment loads predicted to be delivered by river-sediment diversions. This suggests that while hurricanes and tropical storms transport and deposit sediment, the fluvial supply of sediment is more important for the long-term maintenance of a deltaic landscape, which supports the notion that coastal restoration efforts should focus on large-scale diversions to reintroduce river water and sediments to drowned wetlands (Day et al., 2000, 2016b; Kim et al., 2009; Paola et al., 2011; Temmerman and Kirwan, 2015).

3.4. Seasonal inundation and flooding patterns in coastal wetlands

The timing and duration of wetland inundation are key factors in determining wetland productivity and its propensity to vertically accrete at pace with RSLR. Additionally, too little flooding precludes many desirable wetland functions related to fish, wildlife and nutrient removal. Moderate flooding stresses upland plants species so much that wetland plant species can dominate; moderate flooding also stimulates marsh vertical accretion in *Spartina* marshes (Nyman et al., 2006) and in tidal fresh marshes (Cadol et al., 2014). Too much flooding stresses wetland plants so much that they cannot produce the large amounts of peat needed to vertically accrete rapidly (Nyman et al., 2006).

Understanding wetland flooding requires understanding of both water surface elevations and surface elevations. Soil surface elevations are much less dynamic than water surface elevations but the two are related because marsh soil elevations increase, or vertically accrete, in response to inundation up to yet-to-be-identified inundation limits in *Spartina* marshes (Nyman et al., 2006) and in tidal fresh marshes (Cadol et al., 2014). Thus, although the vertical relief in coastal Louisiana is very low, wetland elevation generally is higher where water levels are higher (Fig. 11) and wetland flooding cannot be predicted from either water surface elevations or marsh surface elevations alone. The inactive delta plains of coastal Louisiana typically have lower water surface elevations compared to sites in the Chenier Plain that have equivalent marsh elevations (Fig. 11). The Chenier Plain region (i.e, Calcasieu/Sabine and Mermentau basins) is thus typically inundated for more of the year than much of Louisiana (Fig. 12a).

There is significant spatial variability in the percentage of time that wetlands are inundated in coastal Louisiana (Fig. 12a). The inland swamp regions of Louisiana tend to be inundated for more of the year (percentage time flooded) than the coastal marshes (Fig. 12a), while flood frequency (or number of flooding events) tends to be smaller inland than at the coast (Baumann, 1987). Upstream sites are often isolated from the river, and thus from sediment which can reconvert open water into emergent wetlands and can help such systems vertically accrete at pace with relative sea level rise (eustatic sea level rise plus subsidence; RSLR), which is largely due to subsidence (Conner and Day, 1988). These sites tend to have little salinity and sulfide stress, which

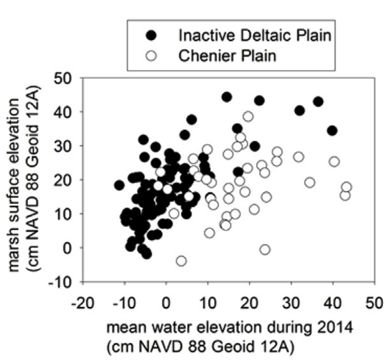

Fig. 11. Relation between water surface elevation and marsh surface elevation at wetland locations across the coastal Louisiana Chenier Plain (n = 42) and Inactive Deltaic Plain (n = 100). Marsh surface elevation was surveyed in 2013; hourly water surface elevations were from the following calendar year. Data were accessed 05 July 2017 from Coastal Information Management System (CIMS) database (http://cims.coastal.louisiana.gov).

enables vegetation to tolerate inundation for a large percentage of year. Accordingly, the average flooding depth associated with inland locations is generally deeper than sites along the coast (Fig. 12b). On average, the coastal region is inundated about 50% of the year, but there exist many sites that are inundated year-round (Fig. 12c). Below we discuss the inundation of a few sites in detail.

In Barataria Basin, flooding duration in swamp regions is generally greater than in saline marshes near the coastline (Fig. 13). The coastal saline marsh is inundated nearly half of the year on average, while the inland swamp forests are inundated far more often than most, as is typical of much of the coastal zone in Louisiana. The flood duration increases moving inland towards freshwater swamp forests, while the flood frequency (or number of flooding events) decreases and becomes less driven by the seasons, tidal variability, and weather events. Because swamps are inundated nearly year-round, there is little to no signal in the flooding frequency for the swamp forests of Barataria Basin. The year-long flooding of such cypress swamps leads to lack of recruitment of cypress seedlings, which advances the degradation cypress forests (Shaffer et al., 2009a,b, 2016; Conner et al., 2014). In contrast to inland swamp forests, Baumann (1987) showed that a coastal saline marsh has an inundation pattern that is modulated by tidal fluctuations and weather events, which results in a largely seasonal percentage of time inundated signal (Fig. 13). Similar behavior is observed throughout the coastal region, including low salinity marshes at the mouths of the active deltas.

Flooding patterns of coastal marshes are impacted by a variety of factors that can lead to increased or decreased flooding. Day et al. (2011) compared total duration of flooding at two marshes (Fig. 14). Marshes adjacent to Old Oyster Bayou (OB) on the eastern side of Fourleague Bay have been impacted strongly by Atchafalaya River discharge for nearly a century. By contrast, marshes adjacent to Bayou Chitigue (BC) in the Terrebonne Basin have been isolated from riverine input for more than a century. The OB and BC sites were flooded about 15% and 85% of the time, respectively, suggesting that the elevation of the BC marsh is near local sea level (Fig. 14). The BC marsh had 187 flooding events in 1993 (some up to 0.40 m) and was never dry for more than 10 consecutive days in 1993. Over the same time period, the OB marsh had less than half of the flooding events, rarely was inundated to a depth of greater than 0.25 m, and was exposed at times for more than 30 days. The OB marsh was regularly inundated only during spring tides during the two Gulf high stands of sea level from April to June and September through October, and was flooded in the winter only during the pre-frontal wind of cold fronts. The spring water level maximum overlaps maximum water and sediment discharge of the nearby Atchafalaya River and provided an opportunity for deposition of river sediments at OB. The BC marsh drained on only one occasion to more than 0.10 m below the marsh surface, while the OB marsh commonly drained below 0.10 m and at one point drained to nearly 0.20 m below the surface. This led to marsh consolidation and increased soil strength at OB (Day et al., 2011).

Outside of the active delta regions, wetland vertical accretion in coastal Louisiana depends upon organic matter produced by marsh vegetation (Nyman et al., 2006). Flooding controls vegetation composition and productivity because flooding prevents plant roots from obtaining oxygen from the soil. When soils are flooded, roots depend upon leaves extending above the water to transport oxygen to roots via stems. Flooding also stresses plants by allowing anaerobic microbes to thrive in soil. Anaerobic soil microbes create numerous substances not found in aerobic soils; some substances can reach concentrations that stress plants such as reduced nitrogen, reduced iron and reduced sulfur compounds. Flooding by fresh water stresses plants less than flooding by sea water because seawater is the primary source of salinity and sulfur to coastal wetland soils. Salt marsh plants can tolerate more sulfide than fresh marsh plants but sulfide toxicity drives salt marsh dieback nonetheless (Koch et al., 1990). Flooding stress is probably more related to length of flooding events than to frequency of flooding

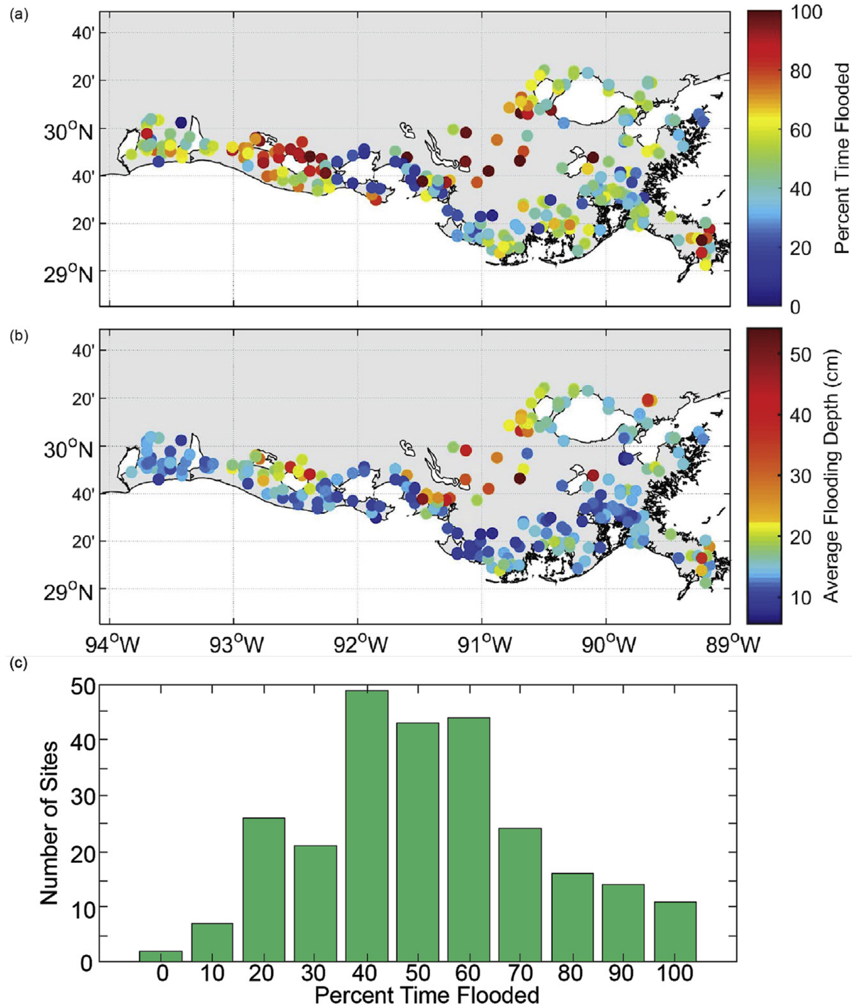

Fig. 12. Inundation patterns for CRMS sites during 2017. (a) The percentage of time that a CRMS station is flooded. (b) The average flooding depth when flooded. (c) Histogram detailing the percentage of time that CRMS sites were inundated during 2017. Data were accessed 01 May 2018 from the CIMS database (https://cims.coastal.louisiana.gov/).

events.

Some observations suggest that low water events are more important than high water events in controlling the duration of flooding. Nyman et al. (2009) found that *Spartina patens* marshes on the central Louisiana coast experienced similar mean daily high-water levels as *Spartina patens* marshes adjacent to Lake Calcasieu even though the former were flooded only 21% of the time but the latter were flooded 32% of the time. Instead of being related to differences in mean daily high-water levels, the difference in flooding appeared related to differences in mean daily low water levels, which averaged 15 cm and 9 cm below local marsh elevation on the central Louisiana coast and adjacent to Lake Calcasieu, respectively (Fig. 15). Moderate flooding stimulates marsh vertical accretion in Spartina marshes (Nyman et al., 2006) and in tidal fresh marshes (Cadol et al., 2014), thus it is not surprising that, except where hypersalinity develops, marshes exist near the upper limit of the tidal range regardless of that range. Consequently, marsh elevation is correlated to water elevations (Fig. 11). Even though sites may all be near mean daily high-water levels, differences in low water levels among marshes should lead to differences in inundation duration and elevation even when other factors are identical, since alterations in tidal range influence water surface slopes, tidal asymmetry, flood/ebb velocities, and, subsequently, channel-marsh morphology (Friedrichs and Perry, 2001). Increases in low water levels should thus increase flooding duration. Increases in tidal range expand growth ranges of vegetation and subsequently, marsh stability (Kirwan and Guntenspergen, 2010), suggesting that higher tidal ranges produce more stable marshes that keep pace with RSLR (Simas et al., 2001; Kirwan et al., 2016). A decrease in tidal range associated with rising low water levels will increase flooding duration and have the opposite effect (Vincent et al., 2013). Factors governing low water levels in marshes vary from site to site because of natural and artificial differences in channel depth between the site and receiving basin. For example, Vincent et al. (2013) noted that plugging ditches did not change high water levels but did increase low water levels and flooding.

3.5. Climate change and sea-level rise

Sustaining the MDR will become more difficult in the face of increasingly severe climate impacts, especially accelerated eustatic sea level rise (FitzGerald et al., 2008; Pfeffer et al., 2008; Vermeer and Rahmstorf, 2009; IPCC, 2013; Tessler et al., 2015; Day et al., 2016a, Fig. 16). Other anticipated effects of climate change on the MRD include more frequent severe hurricanes (Goldenberg et al., 2001; Emanuel, 2005; Hoyos et al., 2006; Webster et al., 2005; Mei et al., 2015; Kossin et al., 2017), floods (Tao et al., 2014; Wehner et al., 2017), floods (Tao et al., 2014; Wehner et al., 2017), droughts (IPCC, 2013; Wehner et al., 2017), an increase in peak Mississippi River discharge (Tao et al., 2014), and more erratic weather in general (Min et al., 2011; Pall et al., 2011; Coumou and Rahmstorf, 2012; Kopp et al., 2017). Between 1901 and 2010, eustatic sea-level rise averaged

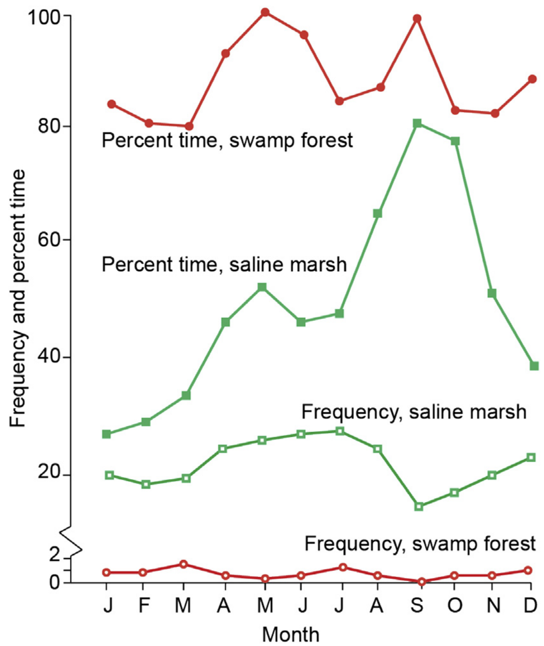

Fig. 13. Comparison of the seasonal inundation regimes of saline marsh and swamp in the Barataria Basin, five-year mean (figure modified from Baumann, 1987).

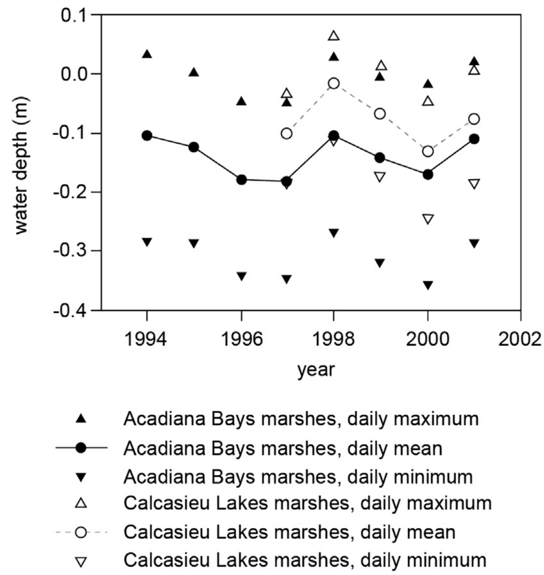

Fig. 15. Annual variability in daily maximum daily depth, daily mean depth, and daily minimum depth of water in marshes adjacent to the Acadiana Bays and to Calcasieu Lake, Louisiana, USA from 1994 through 2004 (modified from Nyman et al. (2009)).

1.7 mm/yr compared to 3.2 mm/yr between 1993 and 2010 (IPCC, 2013, Fig. 16). Thus, the rate of sea-level rise over the past two decades is nearly twice the average of the 20th century as a whole and four times the rate at the beginning of the 20th century. Current projections predict that sea-level rise will reach between 0.3 and nearly 2.5 m by 2100, with a one-meter rise being the most likely (Horton et al., 2014; DeConto and Pollard, 2016; Kopp et al., 2016; Sweet et al., 2017).

Subsidence will heighten problems associated with eustatic sea level rise, leading to substantial RSLR rates in the MDR (Fig. 17; Jankowski et al., 2017). The Northern GOM has relatively high rates of subsidence caused by development of water-drained areas exacerbated by hydrocarbon and groundwater extraction (Kolker et al., 2011) and significant compaction of organic-rich Holocene deposits (Törnqvist et al., 2008). To ensure long-term sustainability, vertical sediment accumulation in a marsh or wetland must keep pace or exceed RSLR. Present-day rates of RSLR in coastal Louisiana are 12 ± 8 mm/yr (Jankowski et al., 2017), with subsidence contributing 9 ± 1 mm/yr (Nienhuis et al., 2017). These estimates are similar RSLR rates of 10.9 and 11.9 mm/yr measured with U.S. Army Corps of Engineers tidal gages at Houma and Eugene Island, respectively (Penland and Ramsey, 1990), which both align with a long-term rate of 9.39 mm/yr established by Gonzalez and Törnqvist (2009). Increases to the tidal prism in Barataria Basin (Kindinger et al., 2013) suggest that changes in tidal range occurring at a similar rate to subsidence also contribute to perceived mean RSLR. Jankowski et al. (2017) used 274 rod surface-elevation table-marker horizon measurements at CRMS stations in coastal Louisiana to determine that much of Louisiana's coastal region lacks sediment accretion that keeps pace with current rates of RSLR. The Chenier Plain in western Louisiana is particularly vulnerable to RSLR due to the lack of sediment input to the region and its unique topographic setting, which leaves another 3000 km^2 of coastal wetland highly vulnerable to drowning (Jankowski et al., 2017). The estimates of Jankowski et al. (2017) are based on data from the last ten years and cannot account for local sea-level variability induced by the 18.6-year tidal cycle and the multi-decadal water level fluctuations affected by the AMO and NAO. In addition, this short time scale may lead to bias in the estimation of regional sea levels, as has been shown along the Dutch coast (Baart et al., 2012), for example, but the estimates of Jankowski et al. (2017) represent the most detailed estimates of spatially-explicit modern RSLR in Louisiana to date.

A marsh surface can be maintained under the influence of RSLR if the rate vertical accumulation is equal to or exceeds RSLR. A recent study suggests that the vulnerability of marshes to SLR may be overestimated since vertical accretion may accelerate with sea level rise (Kirwan et al., 2016). Assessments of vulnerability should consider

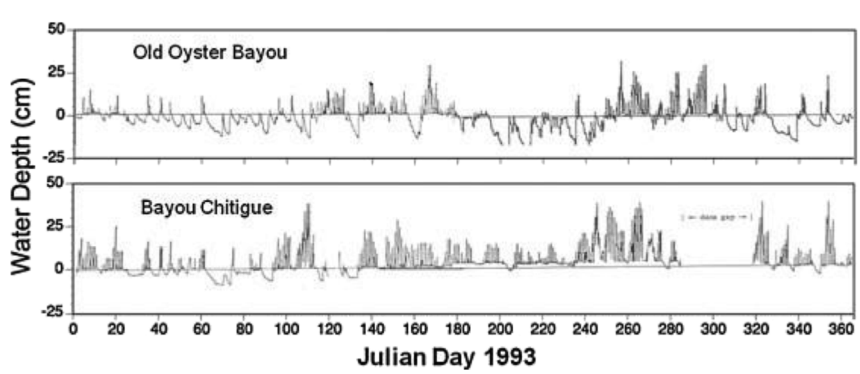

Fig. 14. Water levels at Old Oyster Bayou (OB), which is impacted by Atchafalaya River discharge, and Bayou Chitigue (BC), which is isolated from river discharge. OB and BC are flooded for about 15% and 85% of the time for OB and BC, respectively (modified from Day et al., 2011). Zero is marsh elevation at each site.

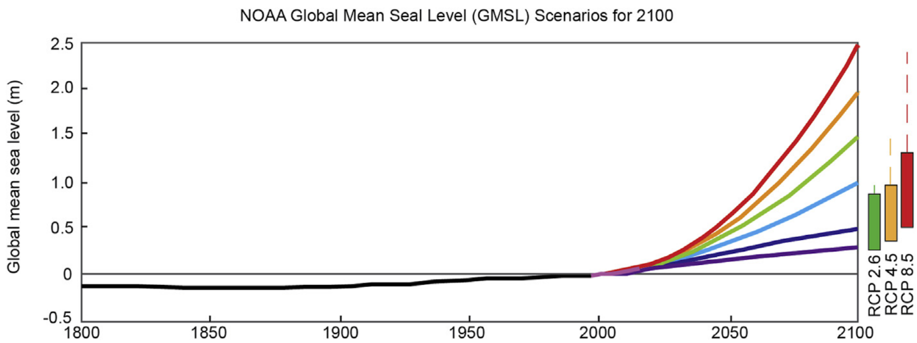

Fig. 16. Global mean sea level (GMSL) data from historical geological, tide gauge, and satellite altimeter GMSL reconstructions from 1800 to 2015 (black and magenta lines) and six future GMSL projections for 2100 (colored lines; from Sweet et al., 2017). The colored boxes represent the 90% conditional probability ranges for three Representative Concentration Pathway (RCP) scenarios that depict different levels of greenhouse gas emissions. The dashed lines indicate the additional GMSL that may occur due to Antarctic melt contributions (Kopp et al., 2014; DeConto and Pollard, 2016), which have yet to be incorporated into probabilistic projections of GMSL. This figure is modified from Sweet et al. (2017).

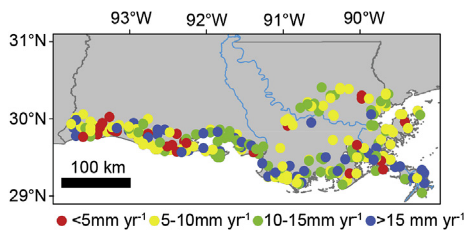

Fig. 17. Current rates of RLSR in coastal Louisiana using calculations from the work of Jankowski et al. (2017).

starting elevation as CPRA's Submergence Vulnerability Index does (Stagg et al., 2013). Areas that are near the top of the tidal frame and are infrequently flooded are less vulnerable than areas that are lower in the tidal frame and are frequently flooded, even if the areas with a higher relative elevation are accreting more slowly than RSLR. However, coastal Louisiana exhibits some of the highest RSLR rates in the world and much of the coastal region is isolated from mineral sediments from the Mississippi and Atchafalaya Rivers that facilitate the vertical accretion needed to restore open water areas to emergent and subaerial wetlands. Vertical accretion of emergent wetlands also depends upon peat production in marshes of the MRD Plain (Nyman et al., 2006), throughout the Gulf coast (Callaway et al., 1997), and on the Atlantic coast (Neubauer, 2008; Boyd and Sommerfield, 2016). The most rapid rates reported in the MRD Plain averaged 9.8 mm/yr with 5 of 15 sites exceeding 10 mm/yr, but RSLR was even faster there (Nyman et al., 1993). The most rapid rates of accretion via vegetative growth reported in the literature were observed in the Sacramento Delta in California where average accretion ranged from 33 to 55 mm/yr (Miller and Fujii, 2011). While increased flooding durations associated with rising waters can increase sediment deposition rates in coastal marsh systems (Kirwan et al., 2016), historic rates of MDR growth (6–8 $km^2\,yr^{-1}$) combined with modern land loss ($\sim$45 $km^2\,yr^{-1}$) and increases in RSLR rates indicate that substantial land loss will continue even under optimistic estimates for land growth due to restoration efforts (Chamberlain et al., 2018). This disconnect is likely due to the relatively low tidal range in the MDR, which limits the effectiveness of rising waters in increase sediment accretion rates (Kirwan et al., 2016). However, Jankowski et al. (2017) calculate that 65% of wetlands in the MDR have sediment accretion rates that allow them to keep pace with modern RSLR, which may indicate that restoration efforts to increase sediment deposition may be successful at abating some wetland loss.

3.6. Human impacts

As indicated in the foregoing discussion, human activity has profoundly altered the MRD, leading to widespread wetland loss and ongoing collapse of the delta. Much of this impact is related to pervasive alteration of hydrology which impacts water level variability (Turner and Streever, 2002; Day et al., 2000, 2012; Ko et al., 2004; Shaffer et al., 2009a,b). Isolation of most of the deltaic plain from riverine input is perhaps the most important hydrologic impact. Lack of riverine freshwater, sediment, and nutrient input exacerbates almost all other environmental issues in the MRD, leading to increasing saltwater intrusion, longer-duration flooding due to lack of sediment input especially where hydrology is altered (e.g., Swenson and Turner, 1987), lack of recruitment in cypress wetlands, lower accretion rates, and diminished wetland productivity (Shaffer et al., 2009a, 2009b; Day et al., 2012; Conner et al., 2014; Snedden et al., 2015).

Pervasive alteration of hydrology in the deltaic plain has led to strong impacts on water level variability. Under natural conditions in the delta, a skeletal framework of barrier islands, Chenier ridges, and distributary ridges limited exchange between fresh and saline parts of the delta. Large north-south navigation channels such as the Mississippi River Gulf Outlet, Calcasieu Ship Channel, and Houma Navigation Canal cut through these barriers and caused regional changes in hydrology, massive saltwater intrusion, rapid drainage of freshwater, and high rates of wetland loss (Britsch and Dunbar, 1993; Shaffer et al., 2009a; Day et al., 2000; Couvillion et al., 2017).

Canals associated with oil and gas exploration and production make up the great majority of the 15,000 km of canals in the coastal zone, and they have had a profound impact on the hydrology of the deltaic plain. They cause direct impacts to wetlands through dredging and the placement of dredged material in spoil banks along canals. In addition, there are indirect impacts of increasing channelization of the marsh that alter surface water hydrology in wetlands (Turner and Cahoon, 1987; Gagliano and Wicker, 1989; Reed, 1995; Day et al., 1999; Ko and Day, 2004; Ko et al., 2004). Oil and gas canals alter natural hydrology because most canals are deep and straight while natural waterways are mostly shallow and sinuous tidal channels (Ko and Day, 2004). Because of this difference, dredged canals tend to preferentially capture flow from natural channels which causes more efficient penetration of salt water into wetlands previously isolated from direct exchanges (Turner, 1987; Wang, 1988; Gagliano and Wicker, 1989; Reed, 1995; Ko and Day, 2004; Ko et al., 2004). Similarly, as canal density increases, the density of natural channels decreases (Swenson and Turner, 1987). While not the primary cause of wetland loss in the MRD, canal construction does contribute to wetland loss in the MRD (Day et al., 2000) and similar dredging activities have been shown to increase long-term water levels in the Pearl River Delta, China, which likely exacerbates wetland inundation (Zhang et al., 2009). Edge erosion is also an important cause of wetland loss (Nyman and DeLaune, 1999; Wilson and Allison, 2008; Mariotti, 2016) and the lack of riverine input due to levees exacerbates the impacts of most other causes (Day et al., 2000, 2007; Paola et al., 2011; Twilley et al., 2016).

Spoil banks are much higher than the natural marsh surface and typically consist of highly organic marsh soil (Day et al., 2000; Reed and Wilson, 2004; Ko and Day, 2004). Because of this, they alter natural sheet flow of water across wetlands and prevent flooding of the marsh which impacts important chemical transformations, flooding of wetlands, sediment transport, wetland productivity, and migration of organisms (Reed, 1995; Gascuel-Odoux et al., 1996; Ko and Day, 2004; Mitsch and Gosselink, 2007). Cahoon and Turner (1989) reported that two hydrologically restricted brackish marshes influenced by a major levee system in southwestern Louisiana showed significantly lower accretion rates when compared to adjacent marshes experiencing direct hydrologic exchange. Networks of spoil banks cause impoundment or semi-impoundment of wetlands (Swenson and Turner, 1987; Boumans and Day, 1994; Day et al., 2000), which results in intrusion and entrapment of salty water, increased waterlogging and decreased drainage, altered sediment flow and decreased accretion, a decrease in vegetation productivity and/or death, and a reduction in the movement of migratory organisms (Turner and Cahoon, 1987; Mendelssohn and McKee, 1988; Cahoon and Groat, 1990; Reed, 1995, 1997; Boumans and Day, 1994; Reed and Wilson, 2004; Olea and Coleman, 2014). Additionally, Swenson and Turner (1987) found that semi-impounded marshes had fewer flooding events compared to marshes with unaltered hydrology (4.5 events vs. 12.9 events), but that the average duration of flooding events was significantly longer (149.9 h vs. 29.7 h) with longer drying events (53.9 vs 31.2 h).

Land subsidence due to subsurface fluid removal has been widely reported worldwide. Subsidence can be increased significantly in the Mississippi delta and elsewhere both during oil and gas production and after production and that wetland loss is higher in the vicinity of oil and gas fields (Sestini, 1992; Morton et al., 2006; Mallman and Zoback, 2007; Dokka, 2011; Kolker et al., 2011; Yu et al., 2012; Chang et al., 2014). Morton et al. (2006) and Mallman and Zoback (2007) reported higher subsidence rates in the vicinity of oil and gas fields with rates as high as 23 mm/yr with total surface subsidence in excess of 1 m over the life of a field. Subsidence often continued for decades after a reduction in production (Mallman and Zoback, 2007; Morton and Bernier, 2010). Processes contributing to increased subsidence in the vicinity of oil and gas fields include slow dissipation of pore pressure (Baú et al., 1999) and creep compaction (Hettema et al., 2002). Yu et al. (2012) suggested that enhanced subsidence was locally related to hydrocarbon production in a field in the Chenier Plain because subsidence increased between 0.5 and 1 m over the period of production for the field. When large volumes of oil and gas are removed, this causes reservoir compaction and/or activating slippage along fault lines (Ko et al., 2004; Morton et al., 2006; Chan and Zoback, 2007, Figure 22). Subsidence and land loss from due to oil and gas production may occur directly above the producing formation or several kilometers away from the producing wells (Morton et al., 2006). Based on analyses of oil and gas production and wetland loss over time, Morton et al. (2006) concluded "wetland loss and fault reactivation typically are attributed to induced subsidence when the area and timing of wetland losses and fault movement coincide with advanced stages of hydrocarbon production".

These relationships among surface alteration of hydrology, enhanced subsidence and wetland loss have led some to conclude that canals have caused almost all wetland loss in the coastal zone (Turner, 1997). However, this is only the case in areas of high oil and gas activity. Edge erosion is also an important cause of wetland loss (Penland et al., 2000; Mariotti, 2016) and the lack of riverine input due to levees exacerbates all other causes (Day et al., 2000, 2007; Paola et al., 2011; Twilley et al., 2016).

4. Implications for restoration

Water level variation in the coastal zone is governed by the combined effects of discharge in the Mississippi River, tides, weather events, climate, subsidence, and human impacts. Because the tidal range is small, weather events and climate assume great importance. Wind regimes are directionally more variable and generally of greater intensity during winter due to frontal passages, leading to strong net onshore and offshore water fluxes. Thus, during winter, there is significant exchange of water between the near-shore region and the shelf, and steady-state flux conditions are infrequent. Riverine input, especially in the Atchafalaya region, can greatly impact this (Twilley et al., 2016). While resuspension and transport of bottom sediments in Louisiana's coastal waters during winter storms and hurricanes can lead to sediment deposition and accretion in the wetlands (Baumann et al., 1984; Turner et al., 2006; Day et al., 2007), practically all coastal sediments in the deltaic plain ultimately come directly or indirectly from the river. Thus, the majority of sediment deposition depends on riverine transport (Coleman et al., 1998; Smith et al., 2015) and fate of much of the deltaic plain in the MDR depends on the effectiveness of riverine sediment diversions in combating wetland degradation and RSLR.

The Louisiana Coastal Master Plan modeling predicts that large diversions along the lower river initially lead to wetland loss due to excessive flooding but will eventually cause net wetland gain (CPRA, 2017), even under high RSLR conditions (e.g., Kim et al., 2009; Rutherford et al., 2018). While there exists ample evidence that riverine sediment diversions can promote sediment deposition and wetland accretion (e.g., Day et al., 2016c, and more), opposition to diversions has developed based on a number of perceived environmental threats including over-freshening of coastal estuaries, displacement of fisheries, potential water quality problems, and assertions that nutrients in river water lead to wetland deterioration (see Day et al., 2018b; Bargu et al., 2019; Elsey-Quirk et al., 2019; this volume for reviews of these issues). In addition, growing climate impacts and growing energy scarcity will make coastal restoration more challenging and limit restoration options (Wiegman et al., 2018; Day et al., 2018a; 2019).

An important issue is the management of diversions to minimize short-term flooding stress while maximizing long-term wetland gain. Both sides of this issue depend in part on water level fluctuations in the areas receiving input from riverine sediment diversions. Results from two marsh sites discussed above (OB and BC) show how the flooding and accretionary history of a marsh site can interact with freshwater introduction from a diversion to enhance sustainability. If the site is already at a high elevation, sediments associated with river water input increases the marsh sustainability. Times of high-water levels, especially associated with pre-frontal winds, lead to high levels of sediment input to wetlands. During low water periods, the marsh consolidates and gains strength (Day et al., 2011). The marshes near Fourleague Bay are at the high end of their elevation growth range and have been so since at least 1950, probably in part because of freshwater, nutrients, and mineral sediments from the Atchafalaya River that slowly increased throughout the 1900s. Additional diversion into such marshes will have a positive impact. Twilley et al. (2016) reported that Atchafalaya River discharge had a positive impact on marshes in a wide arc along the central Louisiana coast where wetland loss is very low. By contrast, marshes like those at BC are at the bottom of their elevation growth range. Additional freshwater, nutrients, and mineral sediments do not lead to elevation gain because of low soil strength and/or low surface elevation combined with increased water levels. Increased flooding will stress these marshes and lead to marsh death and soil column collapse. Snedden et al. (2015) documented that increased flooding from the Caernarvon diversion was the primary cause of marsh loss. This corroborates CPRA modeling that shows that diversions initially lead to marsh loss but in the long-term lead to net marsh gain (CPRA, 2017). This is why CPRA modeling shows that diversions initially lead to marsh loss but in the long-term lead to net marsh gain (CPRA, 2017). Peyronnin et al. (2017) addressed these concerns by discussing ways to optimize diversion operations. For example, they suggested that initial operations should be increased gradually over 5–10 years to facilitate the development of a distributary channel network, reduce flood risk potential to communities, limit erosion of adjacent marshes, and reduce stress to vegetation and fish and wildlife species. They also suggested that such operations should occur in winter to deliver more sediment while protecting marshes and reducing impacts on fisheries and wildlife.

Day et al. (2016a) addressed these issues in the context of an analysis of natural and artificial diversions, crevasse splays, and small sub-delta lobes. They suggested that episodic large diversions and crevasses (> 5000 m^3s^{-1}) can build land quickly while having transient impacts on the estuarine system. They analyzed land building rates for different sized diversions and impacts of large periodic inputs of river water to coastal systems in the MRD and concluded that high discharge diversions operated episodically will lead to rapid coastal restoration and alleviate most concerns about diversions. Single diversion events have deposited sediments up to 40 cm in depth over areas up to 130–180 km^2. An example is the 1927 artificial crevasse at Caernarvon that reached nearly 10,000 m^3s^{-1} and built a crevasse splay of about 150 km^2 and deposited up to 45 cm of sediment in only 3–4 months (Day et al., 2016b). Such large diversions on the Mississippi could also take the pressure off the Bonnet Carré Spillway while building and sustaining hundreds of square kilometers of wetlands. Rutherford et al. (2018) modeled a very large episodic diversion into the Maurepas swamp and concluded that large areas of land could be built and maintained without extended periods of high-water levels. Pont et al. (2017) reported that two large floods in the Rhone delta led to dike failure and deposition of river sediments over a large area of the Rhone delta with accretion rates up to 10 cm. They concluded that the flood events showed that large diversion could enhance the sustainability of wetlands in the delta. Recent experimental work indicates that low discharge periods in deltaic systems tend to drive lateral progradation of deltas, while floods encourage topset accretion (Piliouras et al., 2017). The results of these studies suggest that fluctuations in discharge and inundation magnitudes are necessary for maintaining sustainable deltaic growth.

Monitoring data from the CRMS database (available at https://lacoast.gov/crms2/) indicate that water levels are roughly 40 cm higher in the active Bird's Foot delta than in marshes farther upstream that are currently isolated by levees from direct river flooding but are likely to be flooded by planned diversions (Fig. 12). Thus, it is likely that planned diversions will increase water levels in a similar way. Surprisingly, marsh surface elevations are similar in the active delta and in the currently isolated marshes. Data from CRMS indicate that marshes flooded by the river are flooded in a greater percentage of the year (56% of 2014) than upstream marshes that are isolated from the river (east: 31%; west 39%). This indicates that marshes flooded by the river tolerate greater flooding better than isolated marshes because they are flooded with lower salinity-, nutrient-, and sediment-rich water, and not because they are higher in elevation. Thus, sites currently isolated from river flow but subsequently flooded by a diversion should be able to tolerate the increased flooding but only after soil sulfur pools become like those in the active delta because surface elevations already are similar. Soil total sulfur is approximately 3 times greater in Louisiana salt marsh soils than Louisiana fresh marsh soils (Krairapanond et al., 1992) even without accounting for the 3-fold greater bulk density of the saline soils (Nyman et al., 1990); pore-water sulfate is 5 times greater (Krairapanond et al., 1992) to 26 times greater (Feijtel et al., 1988) in Louisiana salt marsh soils than in Louisiana fresh marsh soils. A diversion likely will reduce surface water salinity and sulfate within days to weeks but it could take years for a diversion to reduce pore-water salinity and sulfide. Increasing flooding before soil sulfur pools become typical of those in low salinity marshes might contribute to marsh losses like those observed downstream of the Caernarvon diversion.

5. Summary and conclusions

Coastal water levels are modulated by a complex suite of processes driven by competing, but interconnected, forces of fluvial, marine, atmospheric, geological, biological, and anthropogenic origins. Understanding the factors driving water level variability should enhance the ability of scientists, engineers, and policy makers to design, manage, and maintain coastal restoration projects. This review provides a detailed synopsis of the factors influencing water level variability in the Mississippi River delta (MRD), an area that has experienced significant degradation over the last century and is currently undergoing a massive restoration and sustainability initiative.

The MRD wetlands developed within the context of this hydrologic and water level variability operating over spatial scales from hundreds to thousands of km^2 and temporal scales from hours to millennia (Day et al., 1995, 2005). During most of its development, the delta was characterized by predictable inputs from the drainage basin, an extremely open system with important exchanges among the river, delta, and coastal ocean; and a relatively stable sea level. This has all changed with reductions in sediment input from the basin, isolation of riverine input from most of the delta plain, and an acceleration of relative sea-level rise due to subsidence and increasing eustatic sea-level rise, which is projected to accelerate during this century and beyond. Accordingly, there is a great deal of variability of water level changes and hydrology across the MRD. This variability is affected by astronomical and non-astronomical forcings at daily, weekly, seasonal, multi-decadal, and long-term time scales. Delta management and restoration must take these spatial and temporal scales into consideration.

River discharge, tides, atmospheric forcings, seasonality, and human activities all affect water levels in the MRD in coastal Louisiana. While changes in Mississippi River discharge can alter water levels significantly (10 + m) throughout the backwater zone, flow spreading at the river mouth dampens the influence of river discharge on water level fluctuations at the coast. Nevertheless, the presence of hydraulic connectivity or lack thereof between the deltaic floodplain and the river affects the timing, duration, and magnitude of wetland inundation. Because the elevation relief in the deltaic plain is low, fluctuations in river discharge can modulate wetland flooding in the coastal zone, as can tides even though the tidal range is small. Because of the microtidal Gulf of Mexico, atmospheric events like winter cold fronts often disrupt water level fluctuations at magnitudes exceeding the largely diurnal tides of the MRD. High water levels associated with feedbacks among multi-decadal water level fluctuations, tidal prism increasing, and barrier island degradation driven by global climate cycles correlate with periods of high wetland loss in the MRD, which highlights the importance of long-term and non-local influences on delta sustainability. Human activities, largely in the form of levees, canal construction, and spoil bank deposition, continue to affect the hydrology of the region and deltas around the world, leading to wetland impoundment and a number of subsequent detrimental effects. Since the MRD experiences one of the highest relative sea-level rise rates in the world, detailed knowledge and predictions of water level variability will become even more important in the future.

Although this review focused on the MRD, it is broadly applicable to deltas worldwide, especially river-dominated systems. The same general patterns of water level variability have been demonstrated for many deltas (Syvitski et al., 2009; Nicholls et al., 2016; Day et al., 2011b). Similar kinds of human impact have also been demonstrated for most deltas including reduction of freshwater and sediment input from the basin (Mekong, Ebro, Nile, Colorado, Indus, Yangtze), isolation of river input from the delta plain (Po, Rhone, Ebro, Ganges, Yangtze), enhanced subsidence (Rhine, Po, Ebro, Nile), pervasive alteration of the delta plain (Rhone, Ebro, Po, Indus, Ganges, Mekong, Yangtze) and widespread reclamation (too numerous to list). Indeed, pervasive alteration of deltas is the rule rather than the exception. Many have concluded that most deltas are not sustainable, especially in their present condition (Syvitski et al., 2009; Renaud et al., 2013; Tessler et al., 2015; Day et al., 2016a,b,c). Thus, enhancing deltaic sustainability hinges on the success of restoration initiatives around the world. The restoration of the MRD can serve as a template for restoration efforts around the world. As described throughout this review, a detailed examination the factors affecting regional and local water level variability, from hourly fluctuations to multi-decadal trends, is integral to understanding and predicting the processes shaping a deltaic landscape.

Acknowledgements

Support was provided by the Louisiana Coastal Protection and Restoration Authority Interagency Agreement No. 4400008905 – Task Order 2, U.S. Geological Survey Ecosystems program, and the National Institute of Food and Agriculture, US Department of Agriculture, McIntire Stennis project, under LAB94095. The authors thank Editor M. Elliott and two anonymous reviews for their helpful reviews.

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